Calculation of the individual and population doses on Danish territory resulting from hypothetical core-melt accidents at the Barsebäck reactor

Jensen, Per Hedemann; Lundtang Petersen, Erik; Thykier-Nielsen, Søren; Heikel Vinther, Frits

Publication date:
1977

Document Version
Publisher's PDF, also known as Version of record

Risø Report No. 356

Risø National Laboratory

Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-melt Accidents at the Barsebäck Reactor

by P. Hedemann Jensen, E. Lundtang Petersen, S. Thykier-Nielsen and F. Heikel Vinther

October 1977

Sales distributors: Jul. Gjellerup, Sølvgade 87, DK-1307 Copenhagen K, Denmark

Available on exchange from: Risø Library, Risø National Laboratory, DK-4000 Roskilde, Denmark

INIS Descriptors

BARSEBAEK-1 REACTOR
BONE MARROW
DATA
DENMARK
FISSION PRODUCTS
GASTROINTESTINAL TRACT
HUMAN POPULATIONS
LUNGS
MAN
MATHEMATICAL MODELS
MELTDOWN
METEOROLOGY
PLUMES
PROBABILITY
RADIATION HAZARDS
RADIATION DOSES
THYRIOD

UDC 519.2 : 614.876 (489) : 621.039.588 (485)

March 1977 Risø Report No. 356

Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-melt Accidents at the Barsebäck Reactor

by

P. Hedemann Jensen, E. Lundtang Petersen

S. Thykier-Nielsen and F. Heikel Vinther

Abstract

Individual and population doses on Danish territory are calculated from hypothetical, severe core-melt accidents at the Swedish nuclear plant at Barsebäck. The release fractions for these accidents are taken from WASH-1400.

Based on parametric studies, doses are calculated for very unfavourable, but not incredible weather conditions. The probability of such conditions in combination with wind direction towards Danish territory is estimated.

Doses to bone marrow, lungs, GI-tract and thyroid are calculated using dose models developed at Risø. These doses are found to be consistent with doses calculated with the models used in WASH-1400.

ISBN 87-550-0495-4

Foreword

In March 1976 the Danish Inspectorate of Nuclear Installations requested the Research Establishment Risø to ".. by means of the best possible documented data, carry out investigations elucidating the consequences to Danish territory of releases of radioactive substances from the Barsebäck plant in the case of reactor accidents with core melt-down. The consequences are required investigated under different weather conditions".

During discussions of the nature and scope of these investigations, the Inspectorate laid weight on having a Danish assessment. The main calculations in the present report were thus carried out using calculation models developed at Risø. Hence, the report includes a detailed description of these models and a discussion of the differences between them and the corresponding American models.

Any Danish assessment of the consequences of the calculated doses to the health of the population must lie with the national health authorities. Thus, on this point the report only gives a very rough estimation based on available American information.

A provisional version of the report was discussed with the Meteorological Institute, who provided significant help through their comments. The Institute also carried out the meteorological calculations for the stations at Kastrup, Gladsaxe and Værløse. However, Risø is solely responsible for the final form of the report.

The authors acknowledge the assistance of the following Risø staff members in the preparation of this report:

N. Abel-Larsen	H.L. Gjørup
Niels E. Busch	F. Højerup
Leif Christensen	Aksel Olsen
Frank W. Cortzen	Vagn S. Pejtersen

The original Danish-language version of the report was published in February 1977 with the number Risø-M-1905.

CONTENTS

APPENDICES

1. INTRODUCTION

An important task in the risk evaluation of an atomic power station is to assess the radiation doses from hypothetical reactor accidents in which radioactivity is released to the environment. For this purpose, calculation models and associated computer programs have been developed at Risø for several years.

The present report evaluates radiation doses to Danish territory from hypothetical core-melt accidents at the Barsebäck nuclear power station situated on the Swedish coast of the Sound some 20 km east of Copenhagen. The evaluation is based on dose calculations carried out by means of computer programs based on Risø's calculation model [1]. For comparison, dose calculations were carried out by means of a computer program (RASDOS 1) based on the calculation model in WASH-1400 (the Rasmussen report) [2, 3]. The WASH-1400 model and Risø's model are described in appendices 1 and 2, respectively.

To give an impression of the sensitivity of the methods applied variations were made in some of the most important parameters. The report further includes an evaluation of the probability of the meteorological situations considered.

2. RELEASE OF ACTIVITY IN CORE-MELT ACCIDENTS

2.1. Accident categories

WASH-1400 classifies the accidents under consideration into categories. Each category represents several different accident sequences, and for each category a total accident probability is given as well as release percentages for the individual isotopes. For boiling-water reactors, these figures are based on a detailed analysis of a large number of hypothetical accident sequences at the Peach Bottom reactor.

Of the accident categories for boiling-water reactors used in WASH-1400, only the first three categories (BWR1, BWR2, and BWR3) imply both core-melt and failure of the reactor containment. Because it is considered that only such categories could cause significant individual doses to Danish territory, the calculations in this report are based on them.

Reference 3 gives a short description of the physical processes defining the three types of accident:

"BWR1

This release category is representative of a core meltdown followed by a steam explosion in the reactor vessel. The latter would cause the release of a substantial quantity of radioactive material to the atmosphere. The total release would contain approximately 40% of the iodines and alkali metals present in the core at the time of containment failure. Most of the release would occur over a 1/2 hour period. Because of the energy generated in the steam explosion, this category would be characterized by a relatively high rate of energy release to the atmosphere. This category also includes certain sequences that involve overpressure failure of the containment prior to the occurrence of core melting and a steam explosion. In these sequences, the rate of energy release would be somewhat smaller than for those discussed above, although it would still be relatively high.

BWR2

This release category is representative of a core meltdown resulting from a transient event in which decay-heat-removal systems are assumed to fail. Containment overpressure failure would result, and core melting would follow. Most of the release would occur over a period of about 3 hours. The containment failure would be such that radioactivity would be released directly to the atmosphere without significant retention of fission products. This category involves a relatively high rate of energy release due to the sweeping action of the gases generated by the molten mass. Approximetely 90% of the iodines and 50% of the alkali metals present in the core would be released to the atmosphere.

BWR3

This release category represents a core meltdown caused by a transient event accompanied by a failure to scram or failure to remove decay heat. Containment failure would occur either before core melt or as a result of gases generated during the interaction of the molten fuel with concrete after reactor-vessel meltthrough. Some fission-product retention would occur either in the suppression pool or the reactor building prior to release to the atmosphere. Most of the release would occur over a period of about 3 hours and would involve 10% of the iodines and 10% of the alkali metals. For those sequences in which the containment would fail due to overpressure after core melt, the rate of energy release to the atmosphere would be relatively high. For those sequences in which overpressure failure would occur before core melt, the energy release rate would be somewhat smaller, although still moderately high."

Table 1. Release fractions from core-melt accidents

Isotope	Release fraction %		
	BWR1 T_k=2h	BWR2 T_k=30h	BWR3 T_k=30h
Co 58	50	3	2
Co 60	50	3	2
Kr 85	100	100	100
Kr 85m	100	100	100
Kr 87	100	100	100
Kr 88	100	100	100
Rb 86	40	50	10
Sr 89	5	10	1
Sr 90	5	10	1
Sr 91	5	10	1
Y 90	0.5	0.4	0.4
Y 91	0.5	0.4	0.4
Zr 95	0.5	0.4	0.4
Zr 97	0.5	0.4	0.4
Nb 95	0.5	0.4	0.4
Mo 99	50	3	2
Tc 99m	50	3	2
Ru 103	50	3	2
Ru 105	50	3	2
Ru 106	50	3	2
Rh 105	50	3	2
Te 127	70	30	30
Te 127m	70	30	30
Te 129	70	30	30
Te 129m	70	30	30
Te 131m	70	30	30
Te 132	70	30	30
Sb 127	70	30	30
Sb 129	70	30	30
I 131	40	90	10
I 132	40	90	10
I 133	40	90	10
I 134	40	90	10
I 135	40	90	10
Xe 133	100	100	100
Xe 135	100	100	100
Cs 134	40	50	10
Cs 136	40	50	10
Cs 137	40	50	10
Ba 140	5	10	1
La 140	0.5	0.4	0.4
Ce 141	0.5	0.4	0.4
Ce 143	0.5	0.4	0.4
Ce 144	0.5	0.4	0.4
Pr 143	0.5	0.4	0.4
Nd 147	0.5	0.4	0.4
Np 239	0.5	0.4	0.4
Pu 238	0.5	0.4	0.4
Pu 239	0.5	0.4	0.4
Pu 240	0.5	0.4	0.4
Pu 241	0.5	0.4	0.4
Am 241	0.5	0.4	0.4
Cm 242	0.5	0.4	0.4
Cm 244	0.5	0.4	0.4

Table 1 shows the release percentages for these three categories of accident as well as the cooling time T_k (the time interval from the shutdown of the reactor to the start of the release) to which the percentages refer.

Calculations of release percentages in WASH-1400 do not consider the condensation and coalescence of droplets in the containment building. A comparison with calculations carried out using the German computer program NAUA [11] seems to show that WASH-1400 significantly over-evaluates the release to the atmosphere.

As a starting-point for the radioactive releases used, the fission product inventory at the Barsebäck reactor was estimated by means of the computer programs FIPO [4] and BEGAFIP [5]. The inventory is calculated on the basis of a burn-up (energy release) of 18 MWd/kg uranium. Appendix 4 shows the inventory of the isotopes of which a percentage is envisaged released in a core-melt accident. The isotopes are the same as those considered in WASH-1400. The inventory is reckoned at different points in time, namely immediately after the reactor shuts down, after two hours, and after 30 hours of cooling. The cooling times are those used in WASH-1400, namely 2 hours for the BWR1, and 30 hours for the BWR2 and BWR3 releases.

The isotope releases for the accident categories under consideration are obtained as a product of the inventory and the release percentages. In the BWR1, BWR2 and BWR3 accident categories, the total activity releases are 529 MCi, 264 MCi and 143 MCi, respectively.

According to WASH-1400, the amounts of heat in the releases are 68 400 MWs, 97 200 MWs and 64 800 MWs, respectively. These figures do not include the release of heat from the accompanying steam through condensation. The release times are, respectively, 0.5 hours for BWR1 and 3 hours for BWR2 and BWR3, cf. the description of the accidents.

2.2. Special features of the Barsebäck reactor

For boiling-water reactors, the WASH-1400 calculations were based on analysis of the Peach Bottom reactor in the USA. The Barsebäck reactor is a boiling-water reactor, but it is not

identical with the Peach Bottom reactor and the relationships between accident probabilities and release percentages can thus differ for the two reactors. Because the absolute accident probabilities are of limited interest for the purpose of this report, no detailed analysis was made of this point.

In the case of a core-melt, the absolute release percentages are, however, significant for the calculation of the magnitude of the radiation doses. Construction differences between the Peach Bottom reactor and the Barsebäck reactor might therefore give rise to a different evaluation of the release percentages.

The two reactors are essentially build on the same principals and there are no differences in the design of the reactor tank or the construction of the reactor core that would definitely affect the course of a core-melt accident. The differences in the two safety systems are of less importance for such an accident, which, of course, implies that these systems fail entirely or partly.

Both reactors are provided with pressure suppression containment. Differences between the relative size and dimensions of the two containments are small and probably unimportant for the course of an accident of the type in question. On the other hand, there are two relevant differences in design:

A. Barsebäck has a wet well located just under the dry well, so that a melted core - in contrast to Peach Bottom - would drop from the floor of the dry well to the wet well basin. On the one hand, this implies a certain risk of a steam explosion in the wet well basin, but, on the other hand, it means that some fission products would be retained in the wet well water.

   In contrast to Peach Bottom - according to WASH-1400 - there is a chance that the Barsebäck containment would remain intact, because the melted core might be cooled in the wet well basin.

B. The Barsebäck containment is made of concrete with a granite aggregate, while Peach Bottom has a limestone aggregate. Thus at Barsebäck there would be no considerable emission of carbon dioxide when the melted core touched the floors or walls. On the one hand this would reduce the activity released when the carbon dioxide bubbled up through the melt

and on the other it would reduce the probability for containment failure as a result of pressure build-up.

Comparisons between Peach Bottom and Barsebäck prove it reasonable to suppose that a core-melt accident at Barsebäck would give a smaller relative radioactive release to the atmosphere than a similar accident at Peach Bottom. However, the present report uses the WASH-1400 release percentages for the Peach Bottom reactor as a probably conservative estimate for Barsebäck.

3. DOSES FROM ATMOSPHERICALLY DISPERSED RADIOACTIVITY

3.1. Dispersion of radioactivity in the atmosphere

In a continuous release of airborne radioactive materials, the activity disperses as a plume in the wind direction. The concentration at the ground at a given distance from the release point will depend on wind speed, atmospheric stability, precipitation, release height, nature of the terrain, physico-chemical form of the activity, heat contained in the release, and the presence of any mixing layers, etc.

The basic dispersion model in the Risø model is the so-called Gaussian model. This assumes that the material is normally distributed around the centre-line of the plume both vertically and horizontally in a plane at right angles to the wind direction [6]. WASH-1400 uses a modified Gaussian model [3], in which the horizontal normal distribution is replaced by a rectangular distribution.

Both models take into account the fact that, as the radioactivity is transported downwind, some of it will be removed from the plume, partly by radioactive decay and partly by deposition (dry deposition) or wash-out during precipitation (wet deposition). Furthermore, the elevation of the plume as a result of its heat content is also taken into account.

The radioactivity released gives rise to three kinds of radiation doses - external doses from the radioactivity in the plume and from the radioactivity deposited on the ground, as well as internal doses from the inhaled radioactivity. Acute injuries may occur as a result of relatively large doses to bone marrow, lungs, GI tract and the thyroid gland.

3.2. Inhalation dose

In the case of an elevated release, the concentration of radioactive material at the ground at shorter distances from the release point will be insignificant. At greater distances the dispersion of the plume in the vertical direction will give rise to significant concentrations at the ground. A person standing here would inhale an amount of radioactivity

proportional to the passage time of the plume and the concentration at the location in question.

The inhaled activity would then distribute itself in the organs of the body, depending on the nature of the material and its chemical form, and later partly decay to stable isotopes and partly be excreted biologically. The inhalation dose is thus absorbed over a period of time that varies from a few weeks to a few years depending on the isotope composition.

People inside buildings are expected to receive a reduced inhalation dose and a delay in the take-up. However, it is difficult to assess these factors, and thus no reduction has been made in the inhalation dose with respect to people inside buildings.

For the accidents in question, the inhalation dose gives the greatest contribution to the total dose to the lungs, GI tract and thyroid gland.

3.3. External gamma dose from the plume

The external gamma dose from the plume is proportional to the passage time of the plume, but in contrast to the inhalation dose it also depends on the concentration distribution of the activity in the vicinity of the location under consideration, as gamma radiation has a considerable range in air.

In contrast to the exposure from inhaled activity, the external radiation exposure ceases when the plume has passed by.

Inside buildings, the external gamma dose from the plume would be considerably reduced because of the shielding effect of the buildings. In calculating the majority of the doses in this report, use has been made of a reduction factor of 0.6 for external gamma radiation from the plume. According to WASH-1400 this value is representative of single-family houses and multi-story buildings of brick [3]. In WASH-1400 it is stated that, on the average, Americans spend ca. 11% of their time out of doors. Taking this feature into account, and also the different types of buildings, an average shielding factor of 0.75 is found for the external gamma radiation from the plume under American conditions. Any possible shift of the average factors to one side or the other, because of a different make-up of building

types and a different outdoors/indoors ratio under Danish conditions, would, however, lie within the uncertainty of a factor of 2 - 3, which must be reckoned with on the dispersion calculations.

3.4. External gamma dose from activity deposited on the ground

While the plume spreads, some of its contents will be removed and deposited on the ground. If precipitation occurs, some of the activity will in addition be washed out and deposited on the ground. The gamma radiation from the activity on the ground will give a radiation dose to a person during the time that he/she is within the contaminated area. The rate of this dose depends on the magnitude of the surface activity at the location itself and its nearest surroundings.

As the ground activity gradually decays to stable isotopes, or is removed by other mechanisms, e.g. wash-off and seepage with rainwater, the dose rate will decline. In contrast to the external radiation from the plume, the external radiation from ground activity also gives rise to radiation doses after the passage of the plume. In addition surface contamination gives rise to internal doses via food-chains. For the accidents under consideration, the external gamma dose from the deposited radioactivity comprises the major part of the total whole-body and bone-marrow dose.

Inside buildings, the external gamma dose from ground activity will be considerably reduced. Using the same source, and based on the same considerations as discussed under 3.3, this report uses a reduction factor of 0.2 for external gamma radiation from deposited activity and an average shielding factor of 0.33 in the majority of the dose calculations. The last factor includes a reduction factor of 0.7 for the dose from deposited activity because of the roughness of the ground [3]. This factor is not included in the factor of 0.2, but it is applied explicitly in all the calculations not describing average situations.

There is a certain doubt, whether or not the factor 0.7 is included in the shielding factor 0.2 in WASH 1400, but it seems from the definition of the shielding factor that it is not.

3.5. External beta doses

The activity in the plume and the activity deposited on the ground emit beta radiation in addition to gamma radiation. However, this radiation is far less penetrating than gamma radiation and therefore only gives rise to skin doses on areas of the body unprotected by clothes. It could be expected that the high energy beta particles contribute to the genetic dose, but calculations show that the genetic dose from beta radiation is without significance.

3.6. Organ doses

Organ doses are reckoned as "acute" individual doses. By "acute" dose is meant the dose which, if it was received within a few hours, would have the same effect with respect to acute injury as the actual dose received.

The acute bone marrow dose is calculated as the sum of the external gamma dose from the passage of the plume, the external gamma dose over 24 hours from the ground activity, the whole inhalation dose in the first seven days, plus half of the inhalation dose from the 8th to the 30th day. The reduction of the inhalation dose from the 8th to the 30th day is due to the fact that a radiation dose received over a period of 2 - 4 weeks is only about half as effective as the same dose received within a few days [3]. The main part of the inhalation dose to the bone marrow is received within the first 30 days.

The acute lung dose is calculated as the sum of the external gamma doses to the lungs and the inhalation dose after 365 days. For the accidental releases under consideration, ca. 80% of the inhalation dose will be absorbed within a year; as the risk of acute injury depends on the rate at which the lung dose is accumulated, this method of calculation gives a conservative result.

The content of the GI tract is normally replaced relatively rapidly, and the inhalation dose to this area will largely be absorbed after a week. The acute dose to the GI tract is therefore calculated as the sum of the external gamma doses to the GI tract and the inhalation dose after 7 days.

For the accidents in question, the inhaled dose to the thyroid gland will mainly originate from the iodine isotopes in the release and, of these, ^{131}I will contribute some two-thirds of the dose. As ^{131}I has a half-life of 8 days and the other iodine isotopes have a half-life of less than one day, the largest part of the inhaled dose will be absorbed after roughly one month. The acute dose to the thyroid gland is thus calculated as the sum of the external gamma doses to the thyroid gland and the inhalation dose after 30 days. The inhalation dose is calculated for adults; the dose for children, depending on their age, can be up to three times as much as for adults.

In calculating latent damage, the dose absorbed from all exposure pathways during the following years, e.g. from the intake of activity via the food-chains, must also be included.

4. METEOROLOGY

4.1. Selection of meteorological situations

In the investigations on which WASH-1400 is based, calculations of doses for many series of observed weather situations made it possible to find a number of accumulated probability functions for doses at a given distance and direction. Calculations of this nature require, however, resources and time that were not available in the present work. Calculations were thus carried out for a series of weather situations known to give large doses and not occurring with negligible probability.

The Gaussian dispersion model includes meteorology both through the wind velocity and through the dispersion parameters. The latter give information on the dependence of the width and height of the plume at a given distance from the source on the prevailing weather situation.

Weather is characterized by seven classes, the so-called Pasquill stability classes A - G, where A is unstable with strong turbulent dispersion and G is stable with weak turbulent dispersion.

An assessment of the calculations shows that by far the greatest part of the probability of receiving relatively large doses originates from weather situations with neutral stability (Pasquill D) and rain. A lesser part of the probability originates from stable weather situations (Pasquill F) with low wind speeds.

In principle, the method gives an under-estimation of the probability, as some contributing cases may have been excluded.

4.2. Dispersion conditions in the Barsebäck - Copenhagen area

The formula sets used by WASH-1400 and the Risø model to describe the dependence of the dispersion parameters on the type of weather and the distance from the source, were established from dispersion experiments made over land. There are no corresponding formula sets for dispersion over water, as only very few diffusion experiments have been carried out here. It is generally assumed that dispersion over water is less than over land because the aerodynamic surface roughness is much less over water.

An assessment of the dispersion conditions in the area between Barsebäck and Copenhagen would, ideally, require many years of meteorological measurements carried out in this area along 200 - 300 m high towers supplemented by numerous series of dispersion experiments.

As this information does not exist, dispersion assessments must be based on knowledge of dispersion over water elsewhere, and on meteorological measurement series made mainly at Risø and at Kastrup.

The Risø data are measured each hour along a 123 m high tower and they comprise wind direction, wind speed and temperature. At Kastrup synoptic observations are made each hour, hereunder wind direction and speed at a height of 10 m.

An investigation carried out by means of satellite pictures of smoke plumes from high stacks placed along the great lakes in the USA [10] states about a case where warm air streams over a cold surface of water: "estimates made by measuring the widths of the visible plume as a function of distance from their sources suggested that while they originally were spreading at Pasquill-Gifford class A,*) after about 30-40 km of over water fetch, they were showing Pasquill-Gifford class F or even G characteristics. This suggests that while the plume originally undergoes rapid mixing due to its own internal turbulence (active diffusion) as well as the turbulence present in the air as it crosses the shoreline (passive diffusion), both processes decay rapidly with overwater fetch, the flow becoming almost "laminar" some tens of kilometers upwind".

The weather conditions that are of interest for dispersion conditions between Barsebäck and Copenhagen are those where the wind is from the east. It will thus have blown over land for some 100 km before reaching Barsebäck and hence the atmospheric turbulent mixing (passive diffusion) of a plume from Barsebäck at a height of 100 m would mainly be determined by thermal and topographical conditions over land. At a distance of 20 km from Barsebäck, conditions over water may also have influenced the dispersion.

---

*) The Pasquill-Gifford classes correspond to the classes denoted Pasquill classes in this report.

It is assumed, however, that any fault resulting from neglecting this influence lies within the uncertainty of a factor 2 to 3, which must be reckoned with on the dispersion calculations under all circumstances.

When the east wind passes Risø, it has blown over land for roughly 30 km; thus in the case of an east wind, the atmospheric parameters measured at Risø may in general be expected to represent the Barsebäck area too.

This fact, combined with the fact that the Risø data include information on meteorological conditions up to a height of 123 m, implies that this is the data set best suited to determine the frequency of the weather situations selected for the dose calculations.

With respect to dispersion conditions at a height of 100 m, it should be noted that calculations involving the Kastrup data can be subject to considerable systematic error because of the variation of wind speed and direction with height.

The following section shows frequencies for different weather situations calculated on the basis of the Risø data, and these are compared with the corresponding frequencies for the Kastrup data. In addition, there are comparisons with measurements made at the television tower in Gladsaxe and measurements from a synoptic station at Værløse.

The purpose of this comparison is to give a conservative estimate of the frequencies of the chosen weather situations and to determine the uncertainties on these. Such an assessment can be made on the basis of the tables given here and in appendix 3.

4.3. Meteorological statistics

Table 2 shows the distribution of wind direction at the three stations Risø, Kastrup and Gladsaxe for all stability classes. The table shows good agreement between the stations.

Table 2

Distribution of wind direction in per cent of time in 30° sectors at RISØ, KASTRUP AND GLADSAXE

STATION	WIND DIRECTION SECTOR											
	0	30	60	90	120	150	180	210	240	270	300	330
RISØ	6.2	5.1	4.1	7.4	9.4	9.1	7.4	10.8	14.0	12.9	7.7	6.0
KASTRUP	6.8	4.3	7.3	7.8	7.8	7.4	7.8	9.2	14.7	14.8	8.8	3.3
GLADSAXE	5.4	5.4	4.4	9.0	7.6	5.8	6.9	8.5	11.0	14.4	14.3	7.3

Time periods and heights of measurements are, respectively, RISØ 1958-1967, 123 m; KASTRUP 1959-1967, 10 m; GLADSAXE 1/3 1974-29/2 1976, 200 m. Wind direction sectors are indicated at the bisector.

Table 3 shows the corresponding distribution for category F+G. It is seen that the frequency of winds in the eastern sector (60, 90 and 120) is 2.0, 1.6 and 0.7%, respectively. The figures illustrate the well-known phenomenon that stable situations occur relatively rarely over large towns because of the heat released to the atmosphere by the town.

Table 3

Distribution of wind directions in per cent of time of 30° sectors at RISØ, KASTRUP AND GLADSAXE
Stabilities F and G

STATION	WIND DIRECTION SECTOR											
	0	30	60	90	120	150	180	210	240	270	300	330
RISØ	0.29	0.35	0.38	0.73	0.93	0.98	0.76	0.65	0.57	0.43	0.20	0.26
KASTRUP	0.71	0.46	0.68	0.46	0.43	0.47	0.75	0.98	1.80	2.58	1.42	0.52
GLADSAXE	0.25	0.38	0.18	0.19	0.33	0.24	0.21	0.14	0.15	0.27	0.17	0.37

The periods and heights of measurements are, respectively, RISØ 1958-1967, 123 m; KASTRUP 1959-1967, 10 m; GLADSAXE 1/3 1974-29/2 1976, 200 m. Wind direction sectors are indicated at the bisector.

In table 4, which shows the distribution for category D, the frequencies in the eastern sector are 12.1, 18.0 and 12.7%, respectively, and 60.3, 72.7 and 58.6% for all wind directions. Risø and Gladsaxe show good agreement. Kastrup shows larger frequencies for stability class D, which chiefly results from differences in the methods of determining the stability classes.

Table 4

Distribution of wind directions in per cent of time in 30° sectors at RISØ, KASTRUP AND GLADSAXE
Stability D

STATION	WIND DIRECTION SECTOR											
	0	30	60	90	120	150	180	210	240	270	300	330
RISØ	3.92	3.32	2.37	4.10	5.67	4.89	4.00	6.38	9.11	8.50	4.47	3.54
KASTRUP	4.65	2.86	5.45	6.34	6.18	5.50	5.79	6.70	10.89	9.94	6.30	2.12
GLADSAXE	2.77	2.75	2.50	5.72	4.51	3.48	4.40	5.42	7.53	8.40	7.79	3.30

Time periods and heights of measurement are, respectively, RISØ 1958-1967, 123 m; KASTRUP 1959-1967, 10 m; GLADSAXE 1/3 1974-29/2 1976, 200 m. Wind direction sectors are indicated at the bisector.

In accidents with long release times and weather situations with weak to steady wind, it would take several hours for the accident cloud first to get out of the Barsebäck reactor and then to move over the Sound and Copenhagen. Wind direction, wind speed and stability conditions would very probably alter during this period of time. Appendix 3 evaluates the influence of these conditions on the frequencies. It is imagined that a "puff" is released from Barsebäck each hour and an investigation is made of how many of these puffs reach Copenhagen. The trajectory down which the puff moves is determined on the basis of wind speed and wind direction measured at one point (Risø, Kastrup or Værløse). If the puff hits Copenhagen within 12 hours after its release, a mean wind speed and mean stability with respect to time are calculated along the trajectories. Appendix 3 shows the

distribution of puff trajectories according to length, speed and stability.

Table 5 shows the frequency of stability classes F and D and of all stabilities. It shows the influence of the height of the observations on the figures, and also that there are variations between the stations. A reasonably conservative estimate can be put at 1-2% for category F and 5-8% for category D. Because D combined with rain is of particular interest in connection with the dose calculations, the frequency of this weather situation is also assessed. The result of the calculations is seen in Table 6. Only data from Kastrup were used, because this station registers precipitation during the observation period. Precipitation measurements are also made e.g. at St. Hareskov, where the intensity of the precipitation is registered continuously, but when this report was prepared, these values were not available in an accessible form; when they are, they can be included in the assessments.

Table 5

STATION HEIGHT (m)		RISØ 123	RISØ 7	KASTRUP 10	VÆRLØSE 10
FREQUENCY IN PER CENT OF PUF-TRAJECTORIES HITTING COPENHAGEN UNDER THE GIVEN STABILITY	F	0.5	2.8	0.7	1.8
	D	4.4	7.4	10.7	10.9
	ALL	12	17	18	20
FREQUENCY IN PER CENT OF TIME WITH STABILITY D AND PRECIPITATION PLUS					
1) WIND SPEED 0-7.5 m/sek				0.9	
2) ALL WIND SPEEDS				2.3	

Time periods of measurements are: RISØ 1958-1967; KASTRUP trajectory calculations 1959-1968, precipitation calculations 1958-1972; VÆRLØSE 1959-1968.

Table 6

Wind speed (m/s)	1	2	3	4	5	6	7	8	9	10
%	0.00	0.00	0.06	0.10	0.21	0.21	0.30	0.35	0.36	0.23
Wind speed (m/s)	11	12	13	14	15	16	17	18	19	20
%	0.16	0.15	0.09	0.04	0.01	0.01	0.00	0.00	0.00	0.00

Distribution in per cent on wind speeds with stability Pasquill D, wind direction from 50 to 100 degrees and precipitation at time of observation. KASTRUP 1958-1972; 116711 observations have been used.

4.4. The influence of averaging time on the time-average concentration

The formula sets used in both WASH-1400 and the Risø model to calculate the dispersion parameters are based on experiments using averaging times from 10 to 60 minutes.

If considerably larger averaging times are used, the width of the plume will be increased and the concentrations correspondingly reduced. This is because the dispersion at averaging times of under 60 minutes is strongly dominated by three-dimensional atmospheric turbulence, while for longer averaging times it is also noticeably affected by larger horizontal eddies.

This condition is taken into account in WASH-1400 where the horizontal dispersion is increased by a factor: (averaging time in hours: 0.5)$^{1/3}$. This procedure has been followed in the Risø model.

Under weather conditions with little wind and stability class F or G, where turbulence is very weak, it is well known that large horizontal eddies contribute considerably to the dispersion. This is often called the "meandering effect" because the large eddies give the plume the appearance of a meandering river. In appendix 3 an attempt is made to assess this effect based on data measured over both sea and land. An increase of the horizontal dispersion by a factor of 4 to 6 at a distance of 20 km seems realistic under stable weather conditions with little wind.

4.5. The height of the plume above ground

The heat contained in the activity release and the speed with which the thermal energy is released, together with the temperature gradient in the lowest layer of the atmosphere, determine the height of the plume. Table 7 gives the values of the release rate of thermal energy P, the release height h and the release time τ for each of the three accident categories under consideration. The table shows the height of the plume Z above ground in the meteorological situations used for the calculations.

Table 7. Distance between plume centre line and ground used in calculations

	Distance between plume centre line and ground (meters)											
	Pasquill A -2.7°C/100m	Pasquill B -1.8°C/100m	Pasquill C -1.6°C/100m	Pasquill D -1.0°C/100m				Pasquill E 0.5°C/100m	Pasquill F 2.75°C/100m			
	u=5m/s	u=5m/s	u=5m/s	1m/s	3m/s	5m/s	9m/s	u=5m/s	1m/s	2m/s	3m/s	5m/s
BWR1 P=38MW h=25m τ=0.5h	-	-	-	948*)	332	209	127	-	-	174	-	-
BWR2 P=9MW h=0 τ=3h	77	77	77	-	129	77	-	92	116	92	80	68
BWR3 P=6MW h=25m τ= 3h	-	-	-	-	126	-	-	-	-	105	-	-

* For other values of wind speed (u_2), the plume distance (z_2) is calculated from:

unstable and neutral conditions: $z_2 = (z_1-h)\frac{u_1}{u_2} + h$

stable conditions: $z_2 = (z_1-h)\left(\frac{u_1}{u_2}\right)^{1/3} + h$

5. PARAMETER STUDIES USING THE WASH-1400 MODEL

The Risø computer program is rather time-consuming in comparison to the program based on the WASH-1400 model. The latter program was therefore used for parameter studies and to select the situations implying the largest doses. These situations were then calculated using the Risø model and the results hereof are included in the conclusion of this report.

The relevant parameters varied are atmospheric stability, wind speed, deposition velocity, wash-out coefficient and accident category. Calculations of bone marrow dose were used in the parameter studies, but any other organ dose would have shown the same influence of the parameters varied.

In contrast to the calculations with the Risø model, which give the doses vertically under the centre-line of the plume, calculations using the WASH-1400 model give the mean doses within a sector width of three times the horizontal dispersion parameter.

5.1. Atmospheric stability

Figure 1 shows the bone marrow dose resulting from a BWR2 accident under varying stability conditions. It appears from the figure that when, as here, there is a hot release, in which the plume rises to a height of ca. 100 m, the largest doses at greater distances occur in the most stable weather situation (Pasquill F). The same applies to BWR1 and BWR3 accidents.

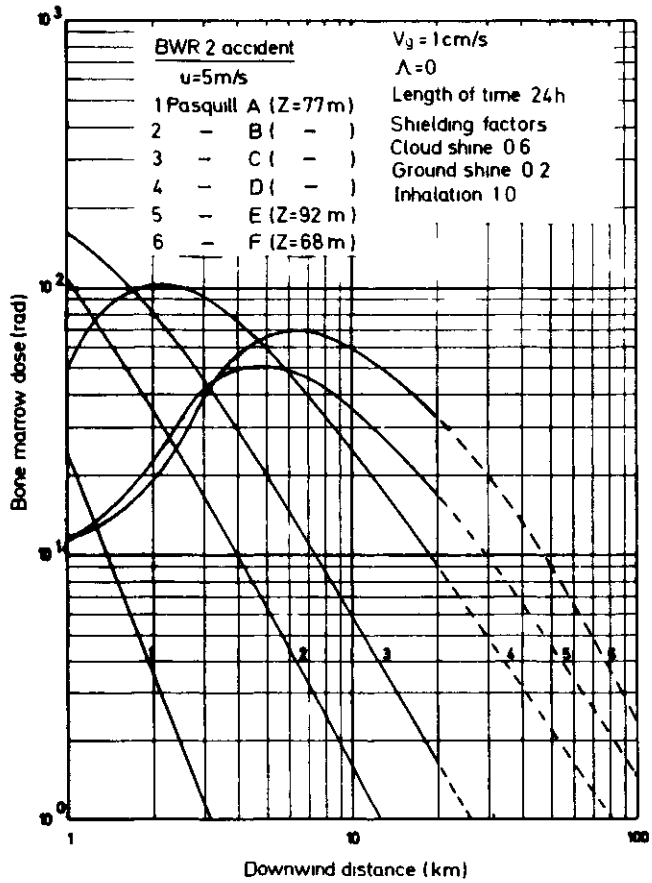


Figure 1 Bone marrow dose from BWR 2 accident under different stability conditions

Assuming no precipitation, the most serious weather situation for dose magnitudes in Copenhagen is Pasquill F. As rain is improbable in connection with stability classes F and E, the following parameter variations were made for weather situations Pasquill F without precipitation and Pasquill D combined with rain.

5.2. Stability class F without precipitation

5.2.1. Acident category

Figure 2 shows bone marrow doses calculated for all three accident categories. It can be ascertained that at a distance of 20 km the BWR2 accident category gives rise to the largest dose. This category is therefore used in the following parameter variations.

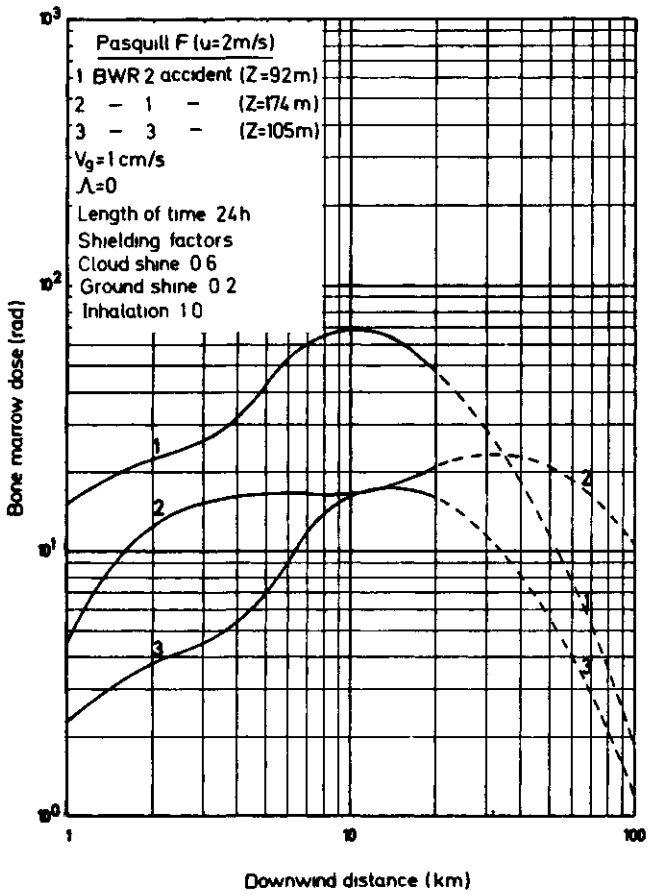


Figure 2 Bone marrow dose from BWR1, BWR2 and BWR3 accidents

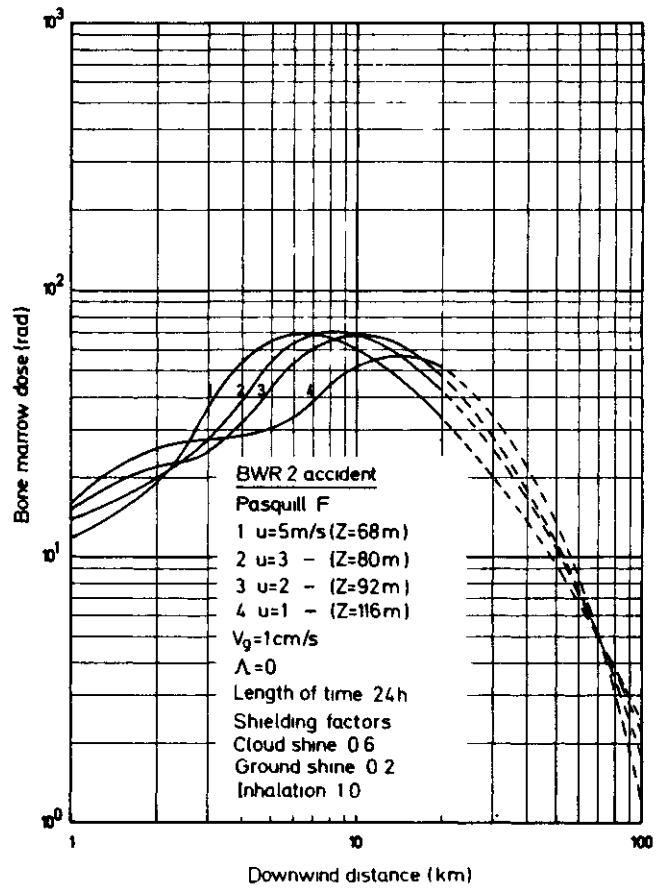


Figure 3 Bone marrow dose from BWR 2 accident at different wind speeds

5.2.2. Wind speed

The influence on dose magnitude of wind speed is primarily the result of its influence on the following quantities: 1) dispersion, 2) rising of the cloud because of its heat content 3) dry and wet deposition of activity from the plume, and 4) magnitude of radioactive decay en route downwind.

For this reason, a change in wind speed can give rise to both increased and decreased doses depending on the distance from the point of release, which appears from figure 3. For the BWR2 - Pasquill F situation, the dose magnitude is, however, relatively unaffected by wind speed.

5.2.3. Deposition velocity

The influence of dry deposition on the magnitude of the doses primarily depends on the height of the centre-line of the plume above ground, but wind speed and atmospheric stability are important too. For the same wind speed and height of centre-line from ground, the significance of dry deposition for the dilution of the plume will decrease when the stability decreases (dispersion increases).

With respect to the importance of plume distance from the ground in general, when the centre-line of the plume is 100 m or more above the ground, the concentration immediately above the ground within 10 - 20 km from the site of the release will, by and large, be unaffected by relatively large alterations in the deposition velocity. This means that the activity deposited on the ground within 10 - 20 km from the release site will be approximately proportional to the deposition velocity. This is illustrated in figure 4. Here it appears that within the first few km from the release site, where the concentration immediately above the ground is practically negligible, the external dose from the plume dominates and this is unaffected by a variation in deposition velocity of a factor of 25. At distances from ca. 3 - 20 km, where the concentration at the ground is of significance, the gamma dose is increased by contributions from the deposited activity which, by and large, increases proportionally to the deposition velocity.

If the centre-line of the plume lies along the ground (cold release), the release is assumed to be in temperature equilibrium with the surroundings, and the dilution of the plume is extremely sensitive to variations in the deposition velocity. In must of these cases the doses are increased when the deposition velocity is reduced, while the dilution of the plume is strongly reduced

when the deposition rate decreases. Figure 5 shows this for a variation of the deposition velocity of a factor 25. The same applies to a hot release at larger distances, cf. figure 4.

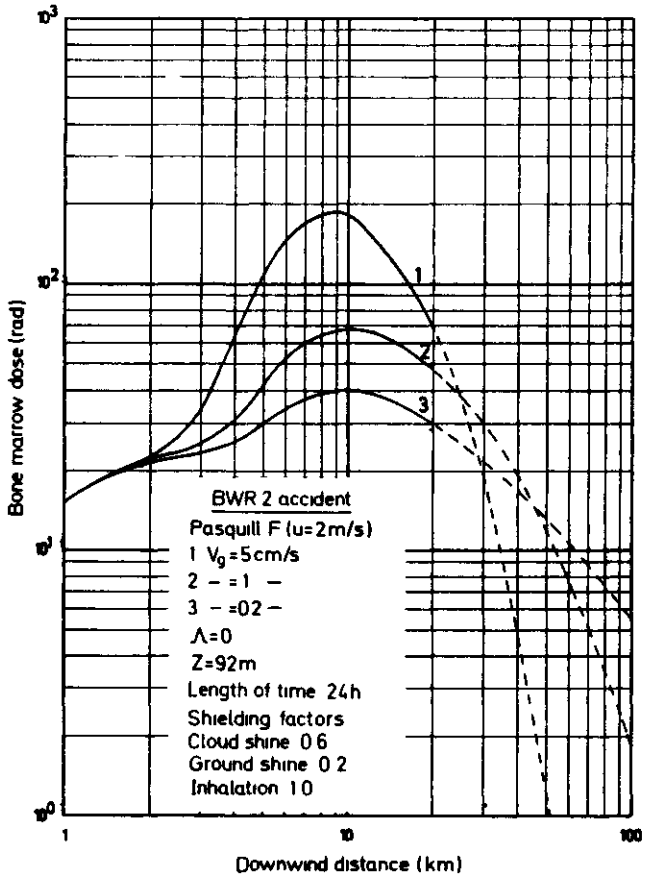


Figure 4 Bone marrow dose, hot release

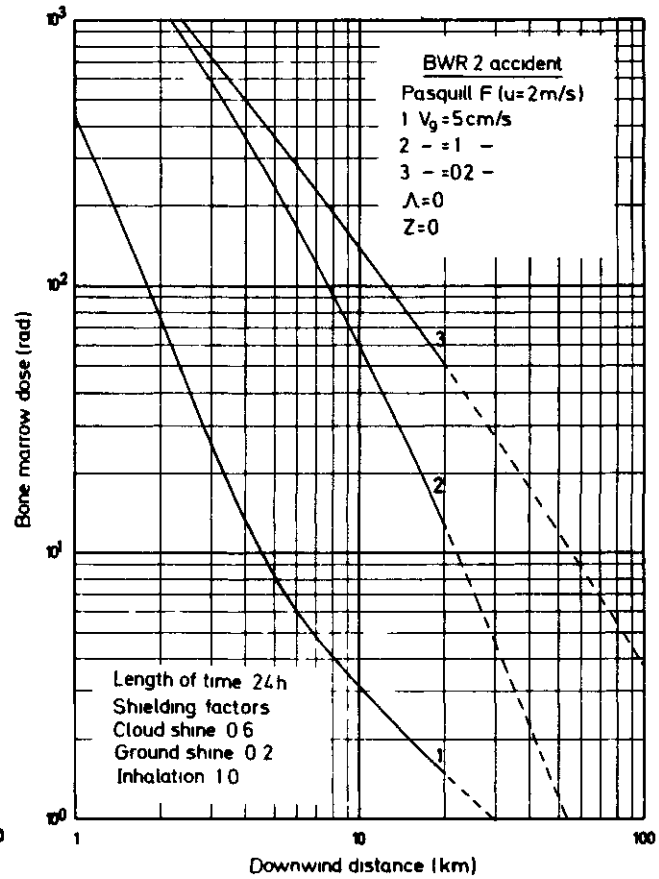


Figure 5 Bone marrow dose, cold release

Hence, if the released activity consists predominantly of depositable isotopes, a cold release under stable weather conditions will give rise to smaller doses at larger distances from the point of release than a corresponding hot release.

Experimental measurements show that the deposition velocity V_g normally lies in the range 0.1-5 cm/s, depending on the roughness of the terrain, the atmospheric stability and the nature of the material in question [7]. All the calculations in this report use a value of 1 cm/s, as is the case in WASH-1400.

5.3. Stability category D with rain

5.3.1. Accident category

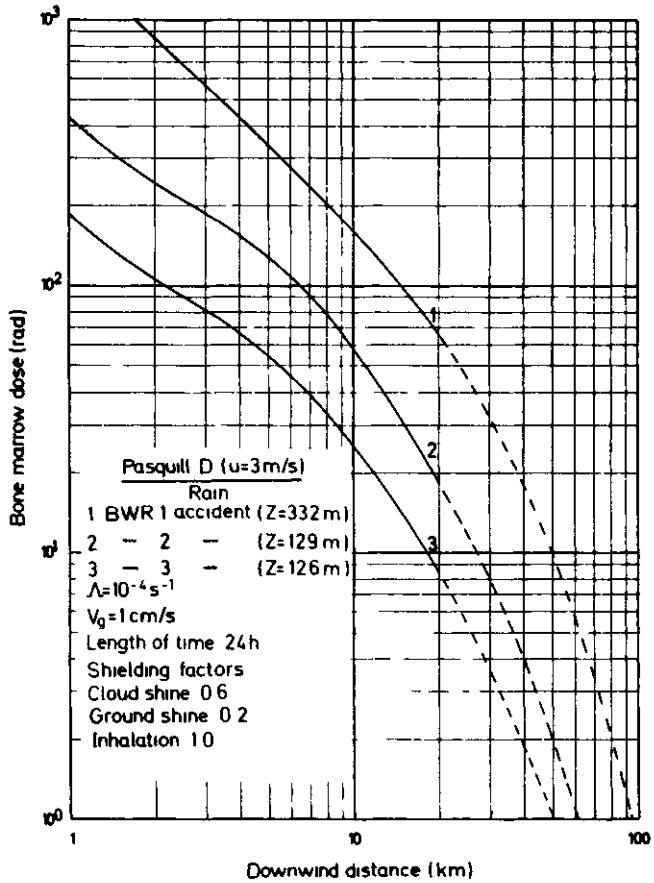


Figure 6 Bone marrow dose from BWR1, BWR2 and BWR3 accidents

Figure 6 shows the acute bone marrow doses from all three types of accident in a weather situation with rain. It is noted that in this situation the BWR1 accident gives the largest dose in contrast to the dry stable weather situation where the BWR2 accident gives the largest dose at a distance of 20 km. This is because, with rain, the gamma dose from the washed-out activity on the ground dominates the total dose even more than the corresponding gamma dose from deposited activity in dry weather. In particular, the difference between the amounts of tellurium in the releases means that the BWR1 accident gives larger doses than the BWR2 accident in weather situations with rain. It should be noted, though, that it is conservatively assumed that all the

washed-out activity remains on the ground and is not partly washed away by the rain.

5.3.2. Wind speed

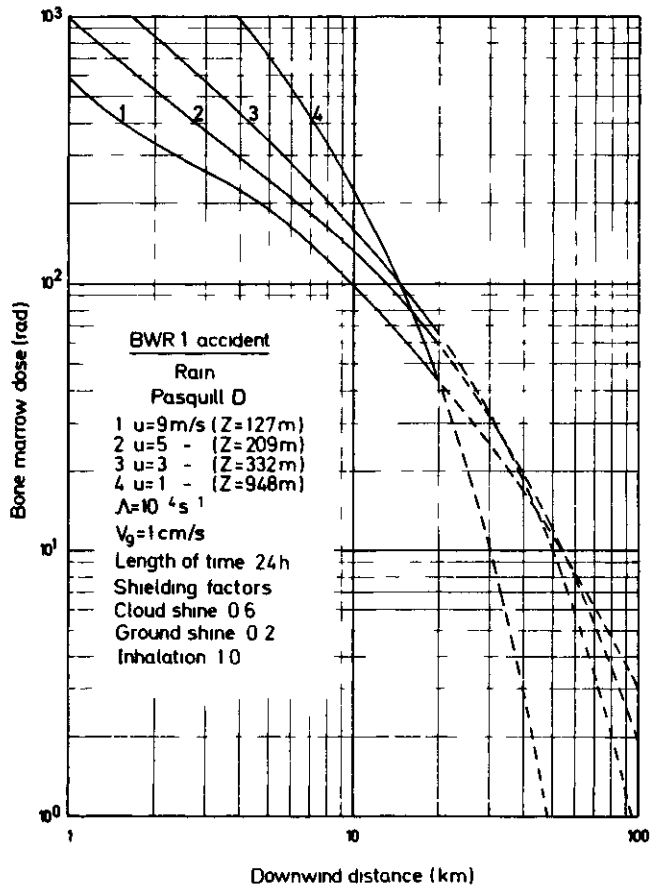


Figure 7 Bone marrow dose from BWR1 accident at different wind speeds

Figure 7 shows the acute bone marrow dose from a BWR1 accident in a weather situation with rain and at different wind speeds. It appears that a wind speed of 3 m/s gives the largest bone marrow dose at a distance of 20 km from the site of the release, but otherwise the influence of wind speed is of minor importance also in this weather situation.

5.3.3. Wash-out coefficient

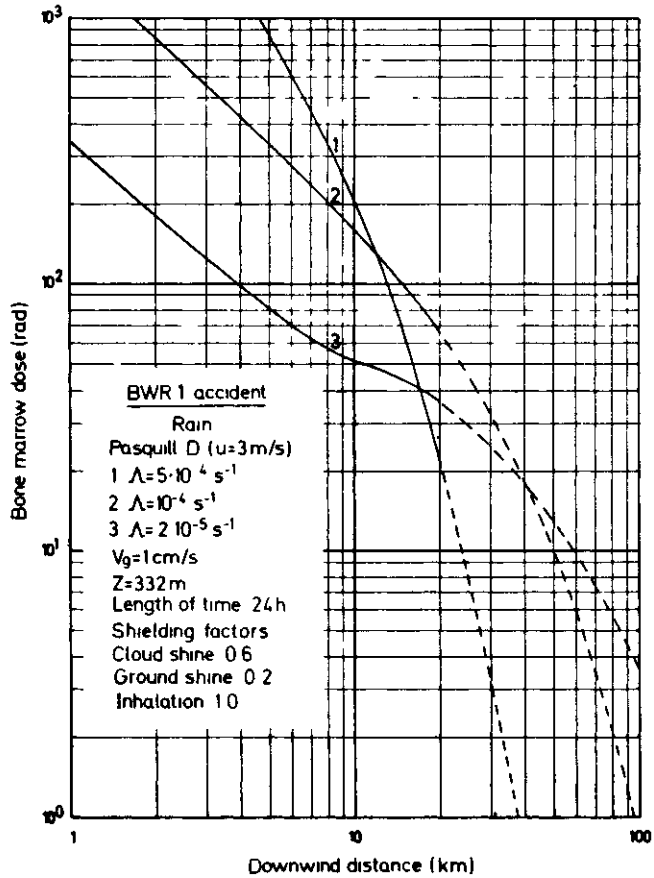


Figure 8 Bone marrow dose from BWR 1 accident at different washout coefficients

Figure 8 shows the influence of the wash-out coefficient Λ on the magnitude of the doses. The same tendency is observed as in the case of dry deposition; namely, that first at greater distances, where the dilution of the plume due to wash-out becomes significant, do the doses decrease with increasing wash-out coefficient. At shorter distances, where dilution is still negligible, the bone marrow dose from the washed-out activity is largely proportional to the wash-out coefficient. Otherwise the height of the plume is not critical, as it is assumed that rain generally falls from heights much larger than the distance of the plume above ground. Washing out thus takes place over the whole height of the plume. The magnitude of the wash-out coefficient is a function of the intensity of the rain and it normally lies in the range 10^{-5} - $10^{-2} s^{-1}$ [3]. A value of $10^{-4} s^{-1}$ is used in all the calculations in this report, just as in WASH-1400.

6. DOSE CALCULATIONS WITH THE RISØ MODEL

As discussed in greater detail in section 4.1, it was not possible - as in WASH-1400 - to calculate doses for a large number of weather situations. Instead, calculations were made of doses for the combinations of accident and weather situation known to give large doses and not to occur with negligible probability.

From the parameter studies discussed in section 5, it appears that the largest bone marrow doses at a distance of 20 km are received from combinations of a BWR2 accident, Pasquill F and a wind speed of 2 m/s, and a BWR1 accident, Pasquill D, with rain, and a wind speed of 3 m/s.

The dose calculations carried out with the Risø model therefore concentrate on these two cases. In addition, however, a calculation was made of the organ doses from the most probable of the three accidents considered (BWR3) in the most probable Danish weather situation (Pasquill D).

The external gamma doses are calculated in air immediately at the surface of the body. These air doses (in rad) are as a good approximation used as external doses to bone marrow, lungs, GI tract and thyroid gland.

All the following illustrations show the doses vertically under the plume centre-line, in contrast to the foregoing illustrations that show the mean doses within a sector width of three times the horizontal dispersion parameter.

6.1. BWR2, Pasquill F

Figures 9 and 10 show, respectively, the distribution of the bone marrow dose on dose components and the organ doses from a BWR2 accident. As mentioned earlier, the doses are calculated for persons inside buildings during the passage of the cloud, who remain there for 24 hours thereafter, and subsequently leave the contaminated area.

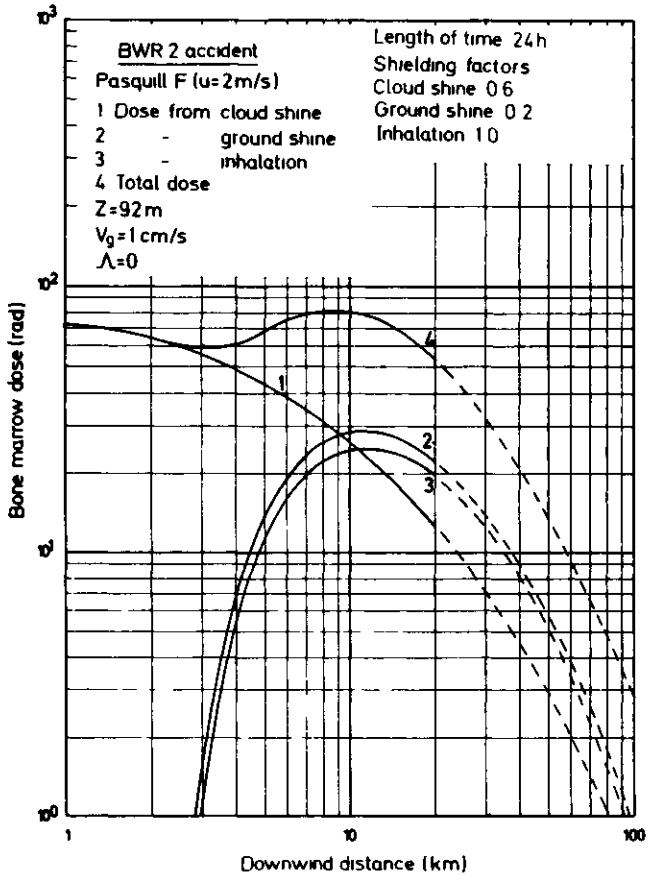


Figure 9 Bone marrow dose from BWR2 accident distributed on exposure pathways

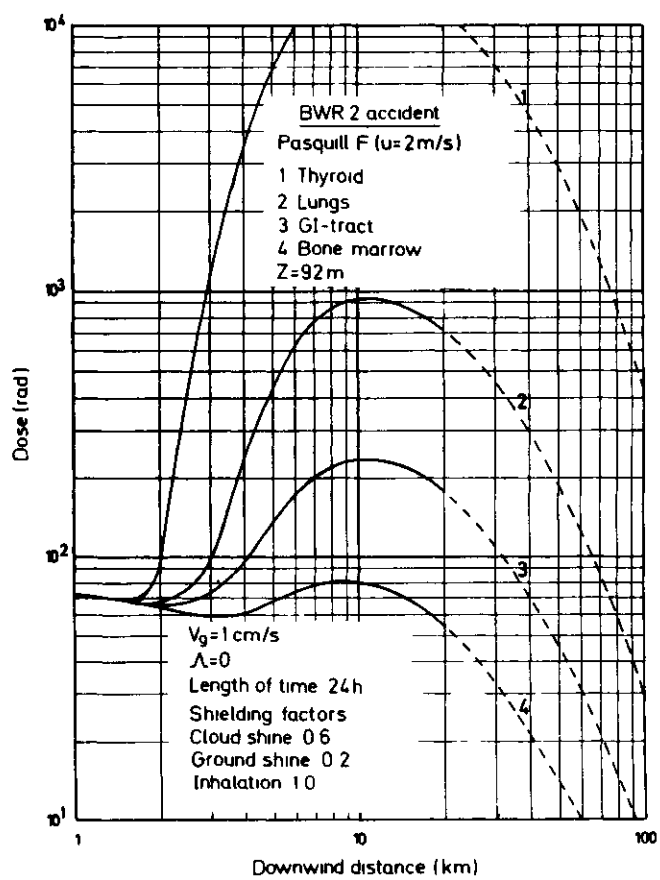


Figure 10 Organ doses from BWR2 accident

The doses from the BWR2 accident are corrected as in WASH-1400, i.e., reduced by a factor $(3/0.5)^{1/3} = 1.82$, because of the three-hour-long release time. In appendix 3 an assessment is made of the effect of the meandering occurring in stable weather situations. This shows that under these conditions doses at a distance of 20 km should rather be reduced by a factor of 4 to 6.

Figures 11 and 12 show the corresponding bone marrow doses 8 and 72 hours, respectively, after the passage of the cloud and for the dose received respectively inside and outside buildings during this period of time.

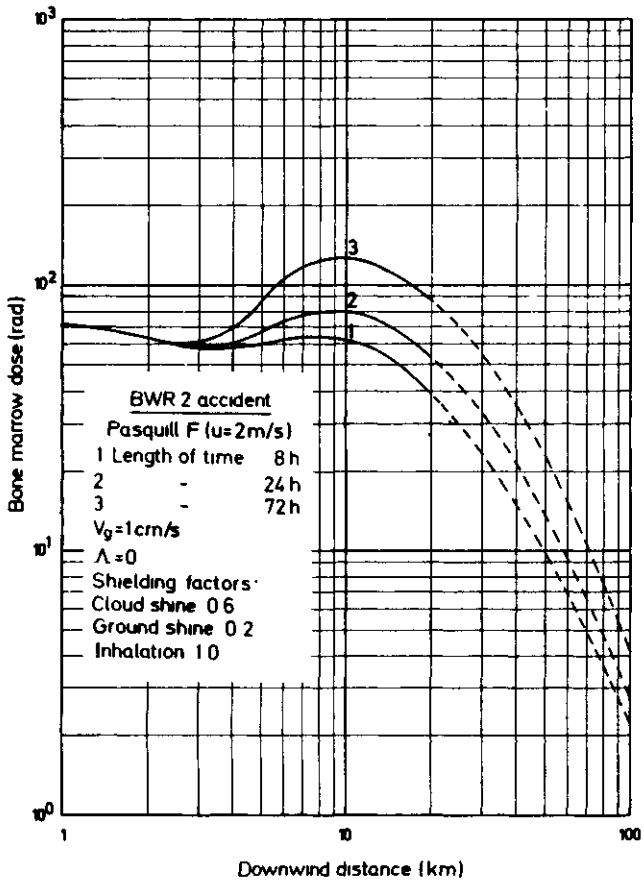


Figure 11 Bone marrow dose from BWR2 accident with shielding reduction

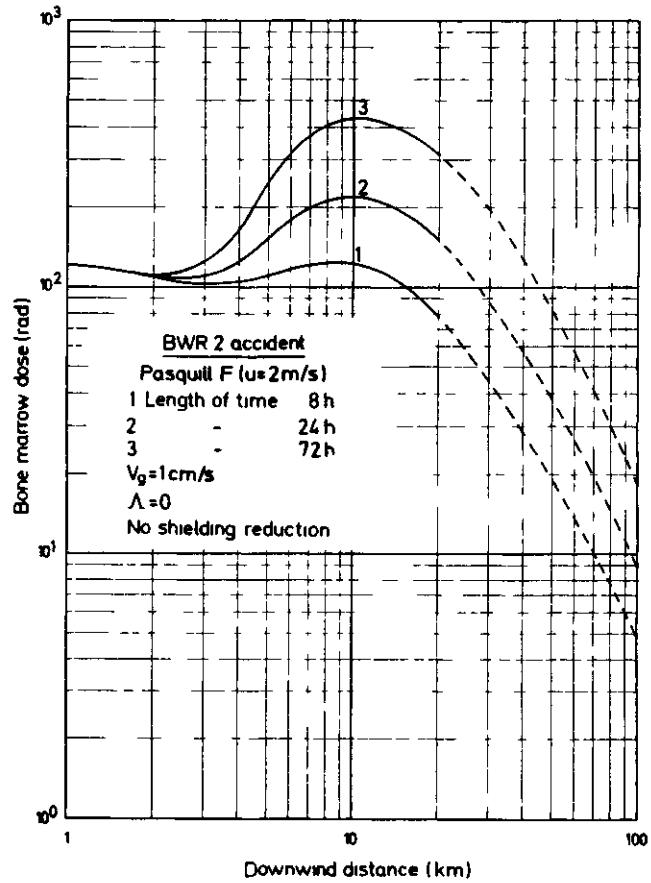


Figure12 Bone marrow dose from BWR2 accident without shielding reduction

The growth of the doses shown on these figures is a result of the gamma radiation from the activity deposited on the ground.

To give an impression of the time variation of the dose from the surface activity, this is calculated for two distances from the point of release as function of time up to 168 hours (1 week) after the passage of the cloud and shown on figure 13.

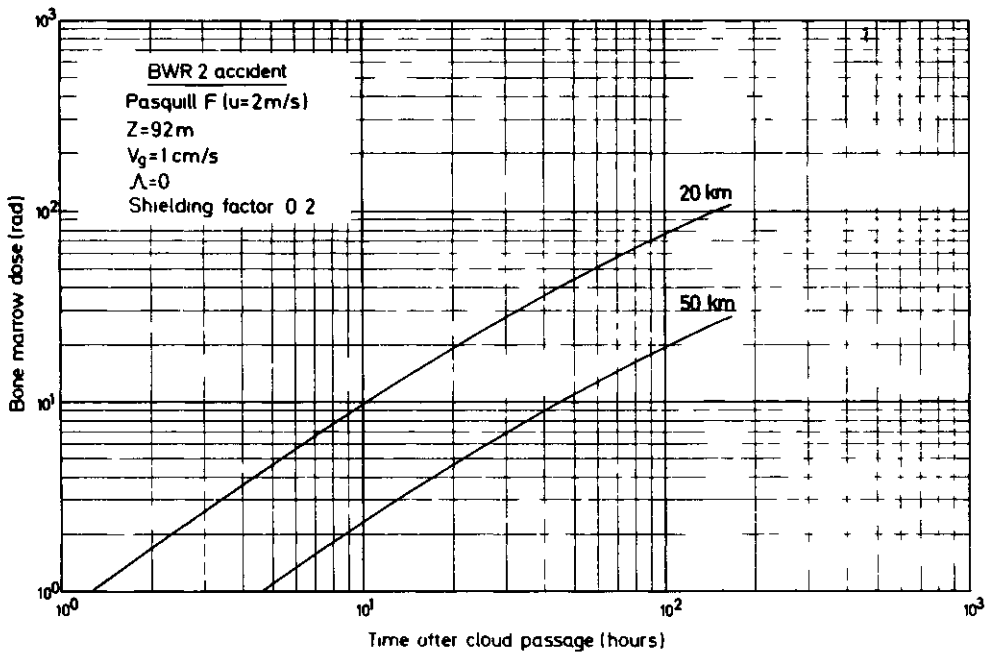


Figure13 Accumulated bone marrow dose from ground shine

The inhalation dose to the bone marrow is calculated as the sum of the inhalation dose after 7 days and the half of the inhalation dose from the 8th to the 30th day after inhalation of the activity.

Similarly, to give an impression of the time variation of the inhalation dose, this has been calculated at 2 distances from the point of release and as function of time up to ca. 30 years after inhalation of the activity; this is shown on figure 14.

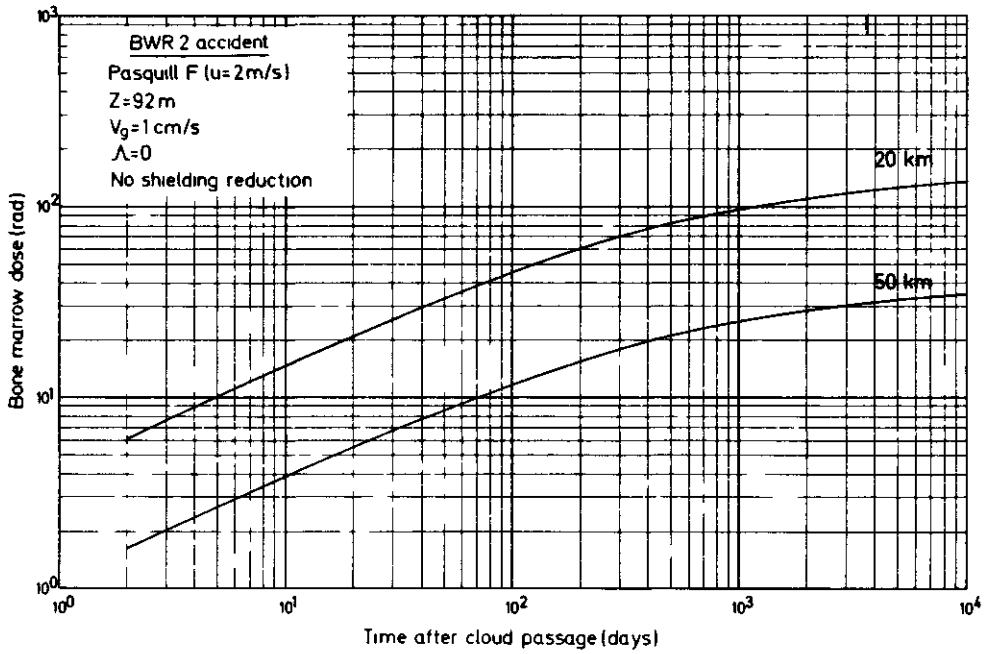


Figure 14 Accumulated bone marrow dose from inhalation

The accumulated population doses from a BWR2 accident are given in table 8 in section 6.2.

As shown in figure 3, the bone marrow dose at 20 km distance is relatively insensitive to alterations in wind speed. The probability for a weather situation that in the case of a BWR2 accident at Barsebäck implies doses in Copenhagen of the same magnitude as shown on figures 9 - 12 will be ca. 0.005, when wind speeds up to and including 5 m/s are included in the probability calculation. The annual probability for receiving the doses in question in Copenhagen is then $3 \cdot 10^{-8}$ when using the accident frequency for a BWR2 accident given in WASH-1400 (one per 170 000 years of reactor operation). The differences between the safety systems at Barsebäck and at Peach Bottom would, however, influence this probability.

6.2. BWR1, Pasquill D and rain

Figures 15 and 16 show, respectively, the distribution of the bone marrow dose on dose components and the organ doses from a BWR1 accident with Pasquill D and rain with a wind speed of 3 m/s. The assumptions regarding residence time are the same as in section 6.1.

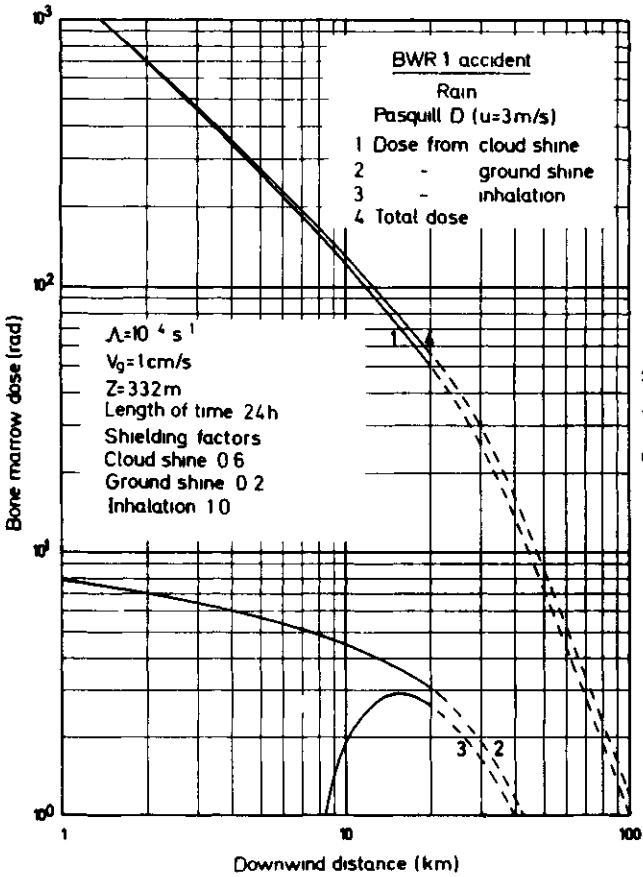


Figure 15 Bone marrow dose from BWR1 accident distributed on exposure pathways

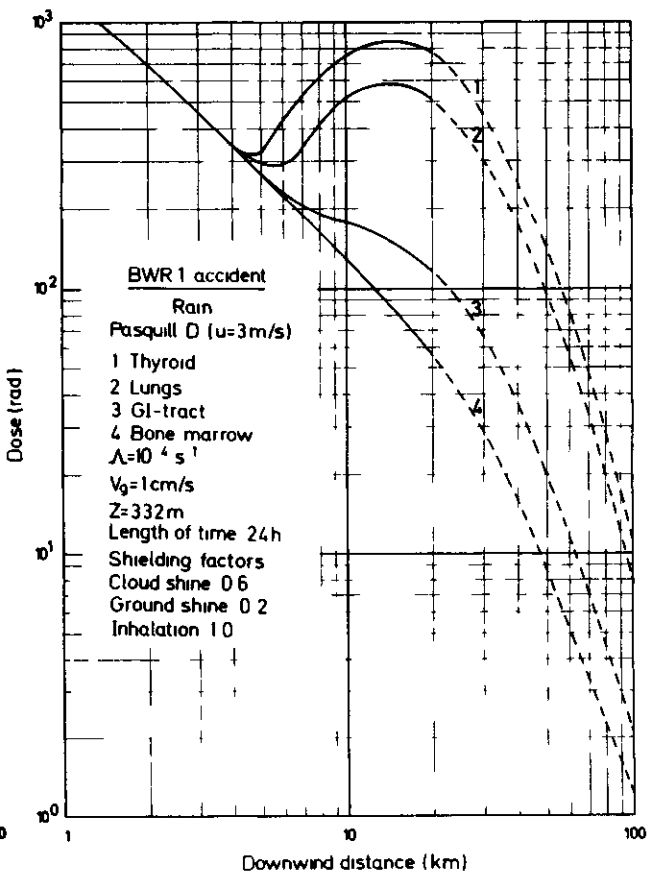


Figure 16 Organ doses from BWR1 accident

Figures 17 and 18 show the doses from the same accident, but relating to times of 8 and 72 hours, respectively, after the passage of the cloud, and for doses received both inside and outside buildings in these periods of time.

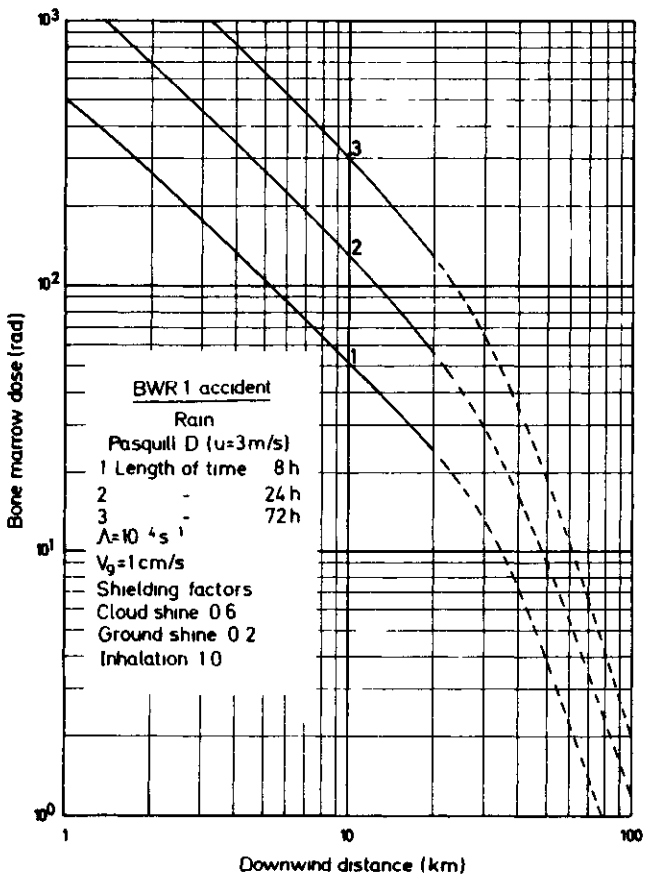


Figure 17 Bone marrow dose from BWR 1 accident with shielding reduction

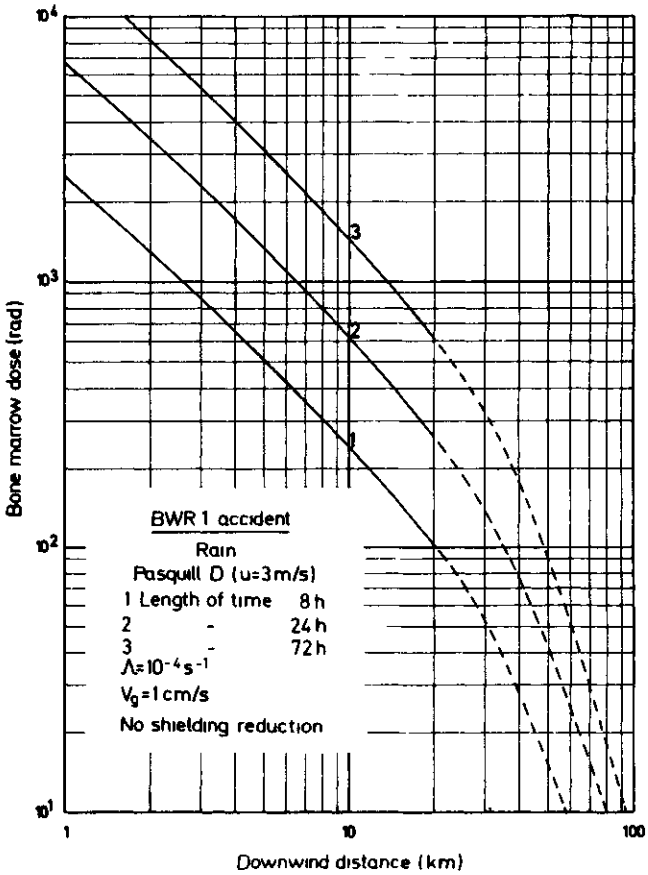


Figure 18. Bone marrow dose from BWR 1 accident without shielding reduction

The bone marrow dose from gamma radiation from the washed-out activity is shown on figure 19 for 2 distances from the release site as function of time up to 168 hours after the passage of the cloud.

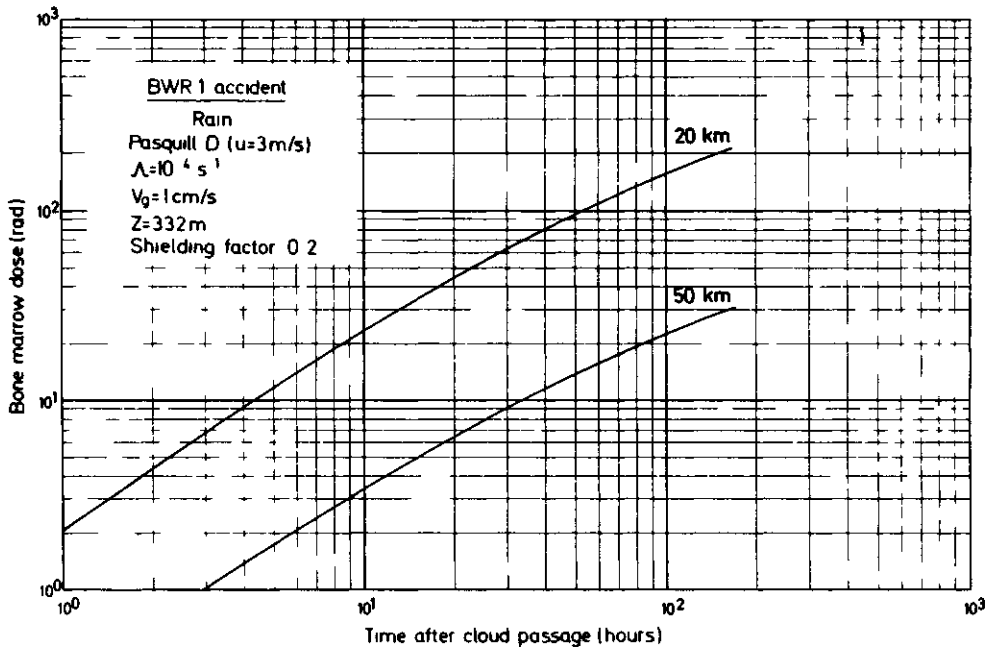


Figure 19 Accumulated bone marrow dose from ground shine

The bone marrow dose from the inhaled activity is shown on figure 20 as function of time up to about 30 years after inhalation of the activity.

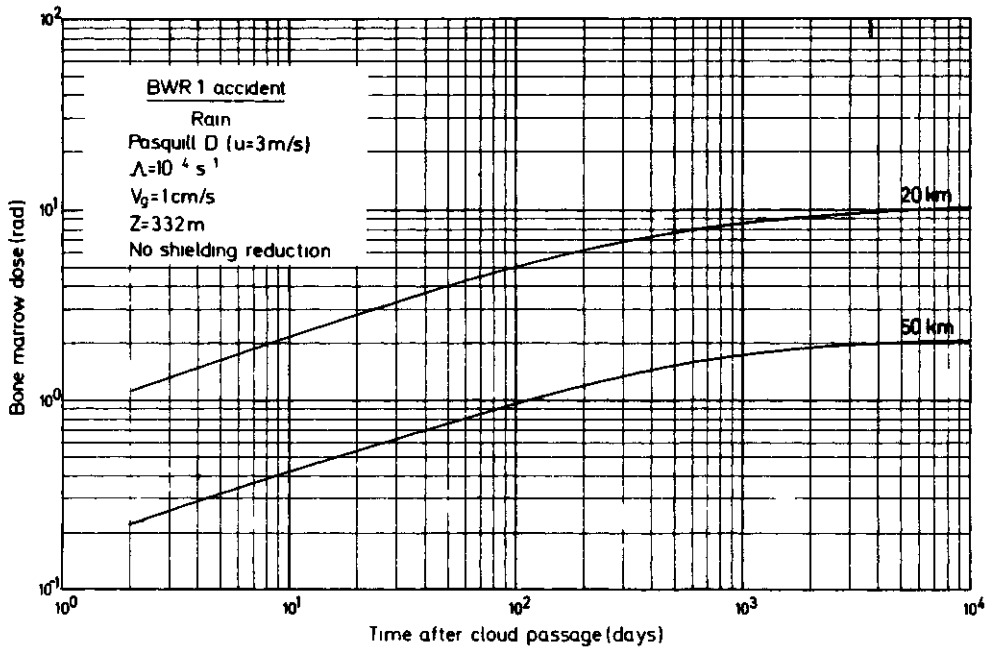


Figure 20 Accumulated bone marrow dose from inhalation

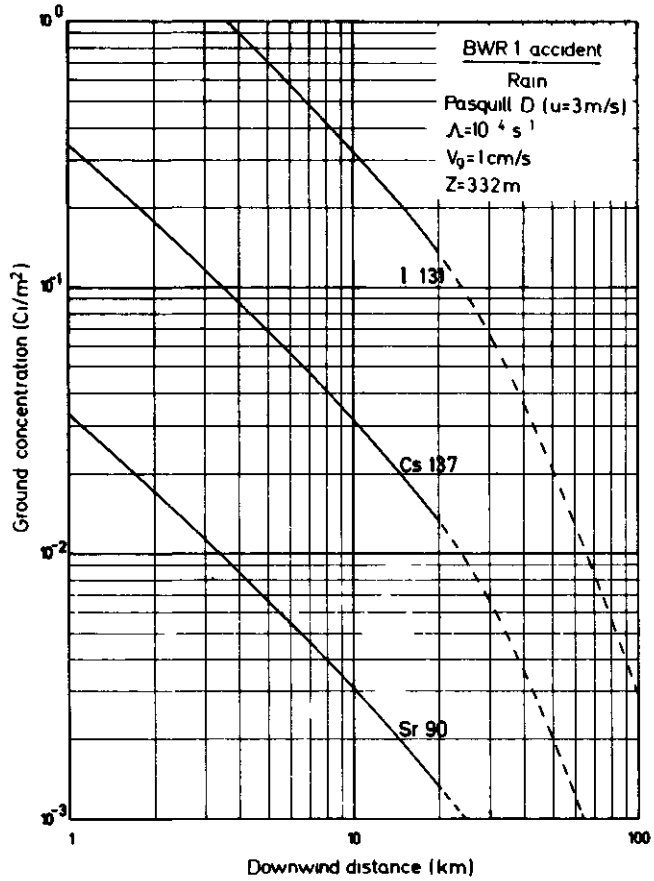


Figure 21 Ground concentration from BWR1 accident

Figure 21 shows the contamination levels in a BWR1 accident for some critical isotopes immediately after the passage of the cloud. If no other measures are taken, the activity level will gradually decrease as a result of radioactive decay and other removal mechanisms, such as seepage with rainwater, etc.

Table 8 shows the accumulated population doses from the BWR1 and BWR2 accidents under the weather situations described earlier. Average shielding factors are used in calculating the population doses (see sections 3.3 and 3.4). The doses shown in table 8 are thus those that would occur in the Greater Copenhagen area provided

that no measures are taken for the first 8, 24 or 72 hours after the passage of the cloud, and assuming an east wind with the given meteorological conditions. Note that the inhalation doses are integrated over 50 years, which implies that the doses for the BWR2 accident become larger than for the BWR1 accident.

Table 8. Accumulated population doses from BWR1 and BWR2 accidents

Population dose (man rad)						
Organ	Residence time after cloud passage					
	8 hours		24 hours		72 hours	
	BWR1	BWR2	BWR1	BWR2	BWR1	BWR2
Bone marrow	1.0 E7	3.3 E7	2.2 E7	4.0 E7	4.9 E7	5.6 E7
Lungs	1.3 E8	1.7 E8	1.4 E8	1.8 E8	1.7 E8	2.0 E8
GI-tract	2.1 E7	3.7 E7	3.2 E7	4.3 E7	5.9 E7	5.9 E7
Thyroid	1.6 E8	2.4 E9	1.7 E8	2.4 E9	1.9 E8	2.4 E9

Inhalation doses are integrated over 50 years
Shielding factors: 0.33 for ground shine
0.75 for cloud shine
The population doses are accumulated to a distance of 100 km's.
The calculation is based on a population forecast for 1985.

For the BWR1 accident, a calculation is made of the beta dose in air at a distance of one meter above the ground originating both from the beta radiation from the plume and from the washed-out activity. This calculation is for a distance of 20 km from the point of release.

The beta energy range for the isotopes in question (0 - 4 MeV maximum beta energy) is divided into 9 energy groups, as shown in table 9, and the distribution of the energy yields of the individual isotopes in these groups is shown in table 10.

Table 9. Maximum beta energies distributed on energy groups

Group no.	Energy band	Group energy (MeV)
1	0 - 0.10	0.05
2	0.10 - 0.20	0.15
3	0.20 - 0.40	0.30
4	0.40 - 0.70	0.55
5	0.70 - 1.00	0.85
6	1.00 - 1.50	1.25
7	1.50 - 2.00	1.75
8	2.00 - 3.00	2.50
9	3.00 - 4.00	3.50

Table 10. Beta particle yields distributed on energy groups

Isotope	Beta particle yield (β-particles dis^{-1})								
	Energy group no.								
	1	2	3	4	5	6	7	8	9
Kr 85				1.0					
Kr 85m					1.0				
Kr 87						0.25			0.75
Kr 88				0.68	0.12			0.20	
Rb 86					0.09		0.91		
Sr 89						1.0			
Sr 90				1.0					
Sr 91				0.07		0.62		0.30	
Y 90								1.0	
Y 91			0.003				0.997		
Zr 95			0.43	0.55	0.02	0.004			
Zr 97							1.0		
Nb 95		0.99			0.01				
Mo 99				0.14	0.03	0.83			
Ru 103			0.99	0.01					
Ru 105						0.89	0.11		
Ru 106			1.0						
Rh 105			0.30	0.70					
Te 127					1.0				
Te 129						1.0			
Te 129m							1.0		
Te 131m			0.04	0.74				0.04	
Te 132			1.0						
Sb 127					0.50	0.20	0.30		
Sb 129							0.20		
I 131			0.12	0.87	0.007				
I 132					0.21	0.39	0.21	0.18	
I 133				0.09		0.91			
I 134						0.38	0.005	0.37	
I 135				0.35		0.65			
Xe 133			1.0						
Xe 135				0.03	0.97				
Cs 134	0.28			0.72					
Cs 136			0.93	0.07					
Cs 137				0.935		0.065			
Ba 140				0.40		0.60			
La 140				0.16	0.12	0.50	0.14	0.08	
Ce 141				1.0					
Ce 143				0.12	0.05	0.77			
Ce 144		0.30	0.70						
Pr 143					1.0				
Nd 147			0.23		0.76				
Np 239			0.41	0.52	0.07				
Pu 241	1.0								

The dose calculation is based on the principles in reference 7. Knowing the distribution of the beta dose in the individual energy groups (for air), it is possible to estimate the magnitude of the beta radiation dose to the skin and to the gonads.

Table 11. Beta doses in air from activity cloud at a downwind distance of 20 km
BWR1 accident - Pasquill D - u = 3 m/s - rain

Isotope	Beta dose (rad)								
	Energy group no.								
	1	2	3	4	5	6	7	8	9
Kr 85				7.84E-3					
Kr 85m					2.47E-1				
Kr 87						3.6E-2			3.02E-1
Kr 88				1.93E-1	5.26E-2			2.58E-1	
Rb 86					2.11E-6		4.40E-5		
Sr 89							4.34E-2		
Sr 90				1.54E-3					
Sr 91				1.75E-3		3.52E-2		3.40E-2	
Y 90								7.00E-4	
Y 91			4.04E-6				7.82E-3		
Zr 95			7.69E-4	1.80E-3	1.01E-4	2.98E-5			
Zr 97							9.68E-3		
Nb 95		8.89E-4			5.09E-5				
Mo 99				4.78E-2	1.58E-2	6.44E-1			
Ru 103			1.58E-1	2.93E-3					
Ru 105						1.23E-1	2.13E-2		
Ru 106			2.52E-2						
Rh 105			2.62E-2	1.12E-1					
Te 127					2.08E-2				
Te 129						6.01E-2			
Te 129m							4.63E-2		
Te 131m			8.01E-4	2.72E-2				6.67E-3	
Te 132			1.94E-1						
Sb 127					8.44E-3	4.97E-3	1.04E-2		
Sb 129							1.26E-2		
I 131			1.05E-2	1.40E-1	1.74E-3				
I 132					4.12E-2	1.12E-1	8.48E-2	1.04E-1	
I 133				2.48E-2		5.07E-1			
I 134						3.27E-2	6.03E-4	6.37E-2	
I 135				7.01E-2		2.96E-1			
Xe 133			8.40E-1						
Xe 135				1.50E-2	7.47E-7				
Cs 134	2.66E-4			7.54E-3					
Cs 136			1.45E-3	1.99E-4					
Cs 137				1.48E-2		2.33E-3			
Ba 140				1.37E-2		4.68E-2			
La 140				5.46E-4	6.32E-4	3.88E-3	1.52E-3	1.24E-3	
Ce 141				3.22E-3					
Ce 143				3.36E-4	2.17E-4	4.90E-3			
Ce 144		2.04E-4	9.52E-4						
Pr 143					4.66E-3				
Nd 147			1.64E-4		1.54E-3				
Np 239			8.43E-3	1.96E-2	4.08E-3				
Pu 241	7.13E-6								
Sum	2.73E-4	1.09E-3	1.27	7.06E-1	3.99E-1	2.02	2.15E-1	4.68E-1	3.02E-1
Total	5.4 rad (E_{max}) - 1.8 rad (E_{mean})								
Sum/ total	5.1E-3%	2.0E-2%	23.6%	13.1%	7.4%	37.5%	4.0%	8.7%	5.6%

Tables 11 and 12 show, respectively, the total beta dose from the passage of the plume and the initial dose rate in air from the ground activity immediately after the passage of the plume. Using the relevant attenuation factors in each energy group from air dose to, respectively, skin dose to the sensitive skin layers (depth 7 mg cm^{-2}) and gonad dose (male) (depth 100 mg cm^{-2}), the following doses are found: 1 rad and 40 rad/h to the skin and 0.1 rad and 6 rad/h to the gonads from the passage of the plume and the surface activity, respectively. These values should

be compared with the doses contributed by gamma radiation, which are ca. 5 rad and ca. 18 rad/h, respectively. It appears that the beta dose does not contribute significantly to the gonad dose, but that, in general, the skin dose is increased by a factor of 3 as a result of the beta dose. It must be emphasized though that it is conservative only to use a depth of 100 mg cm^{-2} in calculating the gonad dose. In addition, the shielding provided by clothing would certainly attenuate more than 100 mg cm^{-2} tissue, so a realistic gonad dose from beta radiation would rather comprise about 10% of the values stated.

Table 12. Beta dose rates in air from deposited activity at a downwind distance of 20 km
BWR1 accident - Pasquill D - u = 3 m/s - rain

Isotope	Beta dose rate ($radh^{-1}$) Energy group no. 1	2	3	4	5	6	7	8	9
Rb 86					7.2E-6		3.5E-3		
Sr 89						1.30			
Sr 90				3.7E-5					
Sr 91				4.1E-5		9.96E-1		4.03	
Y 90								1.03E-1	
Y 91							6.37E-1		
Zr 95				4.27E-5	3.43E-4	8.59E-4			
Zr 97							7.72E-1		
Nb 95					1.73E-4				
Mo 99				1.13E-3	5.35E-2	1.85E 1			
Ru 103				6.91E-5					
Ru 105						3.41	1.65		
Ru 106			∿ 0						
Rh 105				2.68E-3					
Te 127					7.75E-2				
Te 129						2.18			
Te 129m							3.75		
Te 131m				6.39E-4				8.0E-1	
Te 132			∿ 0						
Sb 127					2.86E-2	1.43E-1	8.39E-1		
Sb 129							2.52		
I 131				3.32E-3	5.91E-3				
I 132					3.14E-1	7.29	1.54E 1	2.81E 1	
I 133				5.82E-4		1.63E 1			
I 134						7.78E-1	4.00E-2	6.33	
I 135				1.62E-3		8.31			
Cs 134				1.78E-4					
Cs 136				4.72E-6					
Cs 137				3.49E-4		6.73E-2			
Ba 140				3.25E-4		1.35			
La 140				1.73E-5	2.87E-3	1.50E-1	1.64E-1	2.00E-1	
Ce 141				7.63E-5					
Ce 143				7.92E-6	7.31E-4	1.41E-1			
Ce 144		∿ 0	0						
Pr 143					1.59E-2				
Nd 147					5.22E-3				
Np 239				4.62E-4	1.38E-2				
Pu 241	∿ 0								
Sum	0	0	0	1.16E-2	5.19E-1	60.9	25.8	39.6	0
Total	127 $radh^{-1}$ (E_{max}) 42 $radh^{-1}$ (E_{mean})								
Sum/ Total	0	0	0	0.01%	0.4%	47.9%	20.3%	31.2%	0

As shown on figure 7, the dose to the bone marrow at a distance of 20 km is rather insensitive to alterations in wind speed. The probability of having stability class D with precipitation, a wind direction between 50 and 100° and a wind speed between 1 and 9 m/s can be evaluated with good approximation

on the basis of simple wind rose statistics. Based on measurements at Kastrup (table 6), it can be estimated at 0.016. The annual probability that a BWR1 accident at Barsebäck would give rise to doses in Copenhagen of the same magnitude as shown on figures 15-18 is thus $1.6\ 10^{-8}$, when using the accident frequency for a BWR1 accident stated in WASH-1400 (once per 1 000 000 years of reactor operation). Differences between the safety systems at Barsebäck and Peach Bottom reactors would, though, influence this probability.

6.3. BWR3, Pasquill D

Figure 22 shows the organ doses from the most probable (according to WASH-1400) of the three accidents in question - BWR3 - in the most probable Danish weather situation, stability class D and a wind speed of 8 m/s [8]. According to appendix 3, the probability that the wind would carry the radioactive cloud from Barsebäck to Copenhagen is 0.1 - 0.15, and only under such circumstances would the doses in Copenhagen be of significance.

According to WASH-1400, a BWR3 accident can be expected to happen once on average per 50 000 years of reactor operation.

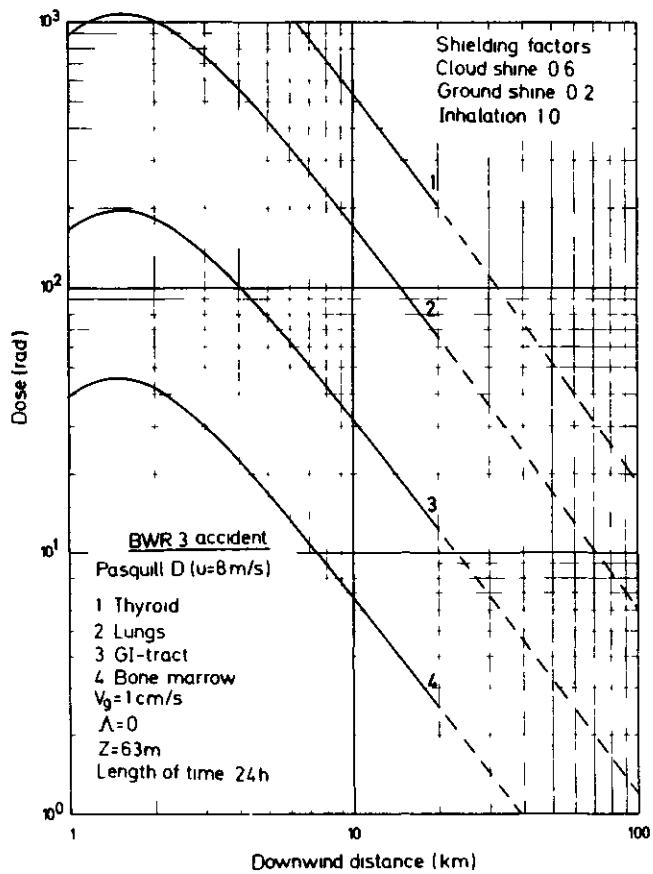


Figure 22 Organ doses from BWR3 accident

7. COMPARISON OF THE RESULTS FROM THE RISØ AND THE WASH-1400 MODELS

A comparison of the bone marrow dose from a BWR2 accident calculated using the Risø and the WASH-1400 models, respectively, is shown on figure 23.

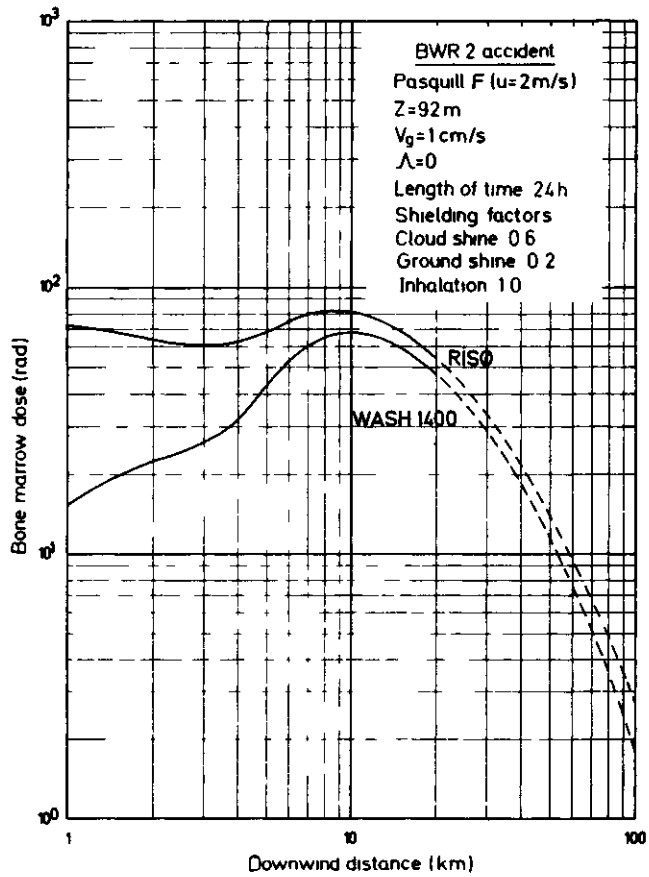


Figure 23 Bone marrow dose from BWR 2 accident

It appears that the dose calculated with the Risø model differs from that calculated with the WASH-1400 model, particularly at short downwind distances. This difference can be ascribed mainly to the following conditions:

1) In WASH-1400 the inhalation rate for adults is reckoned to be 16 l air per minute, while in the Risø model it is estimated at 21 l per minute, as stated in ICRP 2 [9] for an eight-hour working day. Assuming that people are more active in an accident situation, WASH-1400 uses an inhalation rate that is 15% larger than the average for the whole day, while the Risø model uses the rate applying to a work situation.
2) The activity concentration at the ground calculated from the WASH-1400 model is reckoned to be ca. 84% of the corresponding concentration under the centre-line of the plume using the Risø model. WASH-1400 assumes, that the concentration is constant across the wind direction within a sector width of three times the horizontal dispersion parameter. The Risø model assumes a Gaussian distribution across the wind direction. Along the edge of the sector used in WASH-1400, the concentration calculated using the Risø model is ca. 38% of the corresponding concentration calculated using the WASH-1400 model.
3) Differences between dose-conversion factors from surface activity to dose rate, hereunder contributions from backscattering, that are not included in the Risø model.

If the Risø model had used the same dispersion model, the same inhalation rate, and the same dose-conversion factors from surface activity to dose rate as in WASH-1400, the inhaled dose and the external gamma doses, shown on figure 9, would have been 1.57 and 1.19 times smaller, respectively.

Even taking the above conditions into account, there is still a considerable difference between the external gamma doses from the passage of the plume at short downwind distances. This must be ascribed to the different calculation methods. The Risø model makes a spatial integration of the volume of the plume, whereas the WASH-1400 model, as an approximation, uses a correction factor describing the relationship between the dose from an infinitely large cloud containing uniformly dispersed activity and the dose from a corresponding cloud of finite dimensions.

Because the method of calculation in the Risø model is more mathematically correct than the approximation of the WASH-1400 model, the external gamma doses from the plume calculated from the Risø model must be the most correct. Figure 24 shows there is better agreement between the corresponding calculations of the bone marrow dose from a BWR1 accident. The difference here can be ascribed to the above-mentioned conditions, especially point 3.

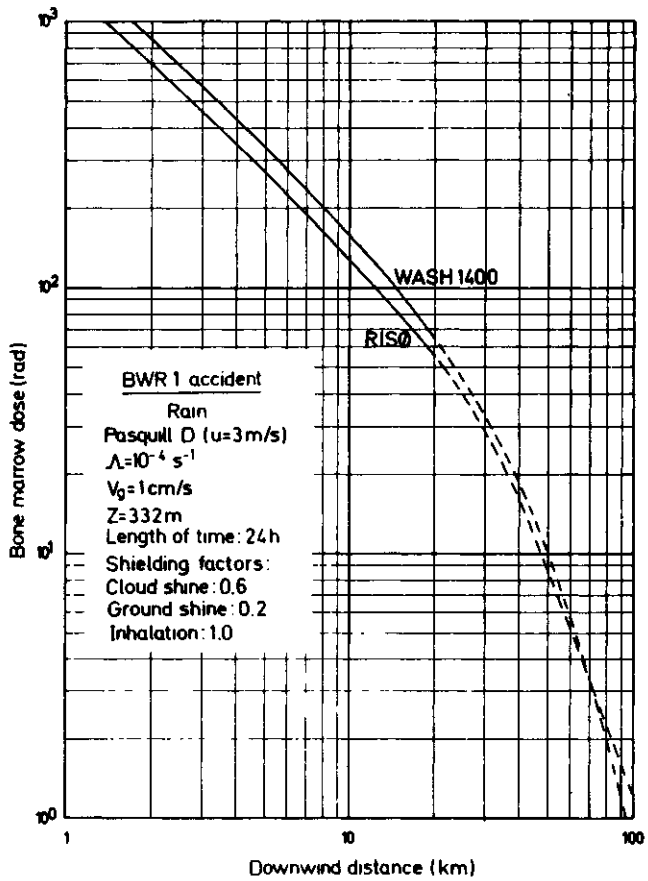


Figure 24. Bone marrow dose from BWR1 accident

In contrast to the WASH-1400 model, when calculating the amount of activity deposited on the ground, the Risø model takes into account the decay of the deposited activity, and also the build-up and decay of the daughter products of the deposited isotopes during the period of the release. This difference, which could specially apply to the three-hour-long BWR2 accident, is, however, unimportant for the results of the foregoing calculations.

8. SUMMARY AND CONCLUSION

8.1. Dose calculations

The doses that would be possible on Danish territory as a result of an accident at the Barsebäck plant are calculated for the most unfavourable, but not utterly improbable, weather conditions. The doses are calculated on the basis of releases of radioactive materials from a boiling-water reactor; these releases are described in the final version of WASH-1400 for different hypothetical accidents. Individual doses from these activity releases are calculated both on the basis of Risø's own calculation methods and on those of the Rasmussen report - the latter in the form of the computer program RASDOS 1. The two methods give results that agree for distances corresponding to the distances from Barsebäck to Danish territory. For shorter distances, the Risø model is assumed to be more realistic.

Figures 25, 26 and 27 show the extent, with respect to area, of the dose distributions giving the greatest acute bone marrow doses at a distance of 20 km from Barsebäck (BWR1 accident, cf. fig. 17). The doses decrease relatively rapidly when moving away from the centre-line of the plume across the wind direction.

The curves on figs. 25, 26 and 27 cannot be extrapolated over the Sound because no layer would be deposited on the surface of the water in the same way as on the ground.

8.2. Evaluation of the significance of the calculated doses

The probability that bone marrow doses of the magnitude given on figs. 9 and 15 for a distance of 20 km, would imply acute fatalities must be considered small - even when taking into account the uncertainty on the calculated doses. Otherwise, the probability partly depends on the general condition of the individual and partly on any subsequent medical treatment. WASH-1400 describes two different relationships between the magnitude of the bone marrow dose and the probability of acute fatalities within 60 days.

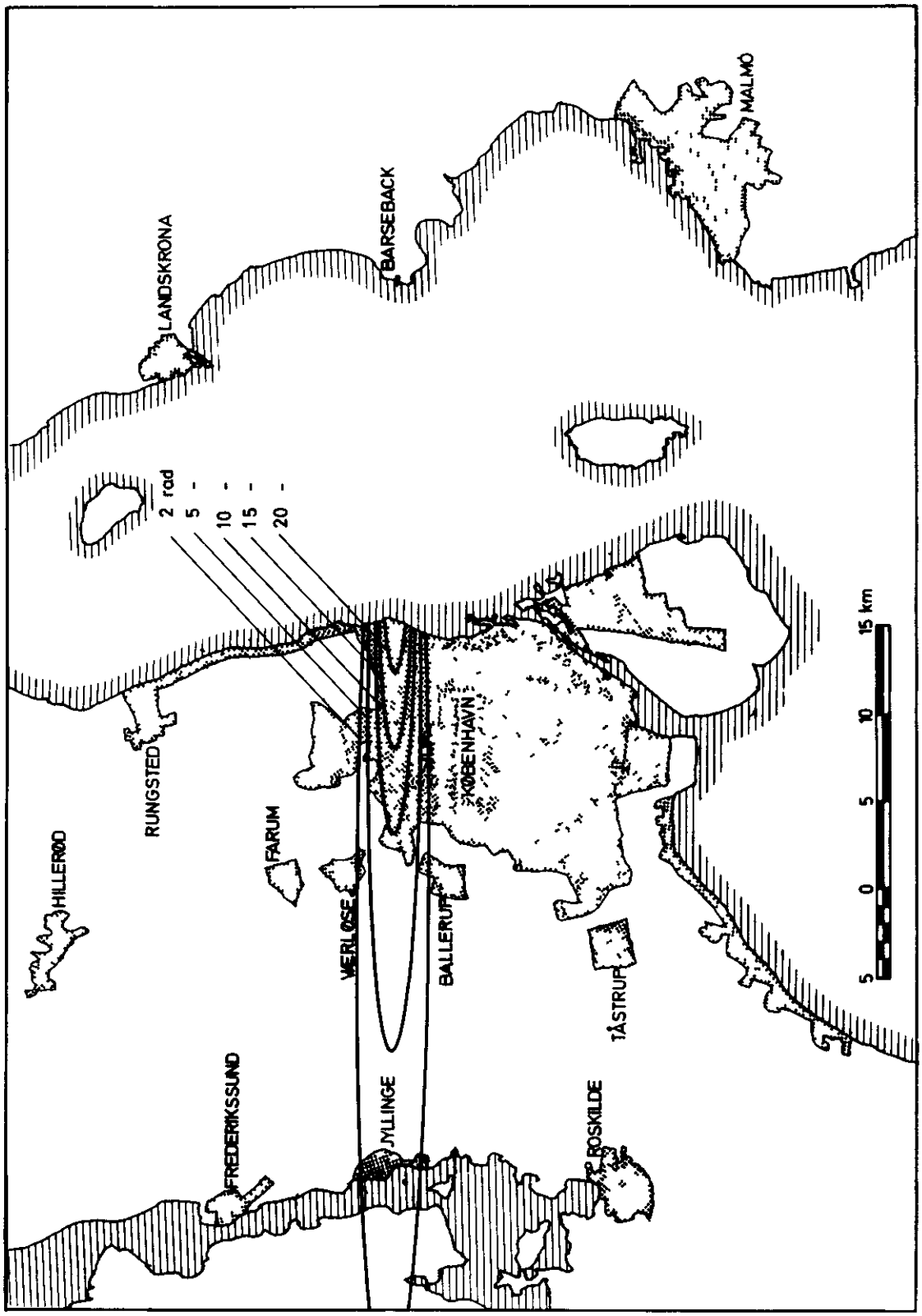


Figure 25 Shielded bone marrow doses from a BWR1 accident 8 hours after cloud passage
The meteorlogical conditions are Pasquill D, rain, wind speed 3m/s

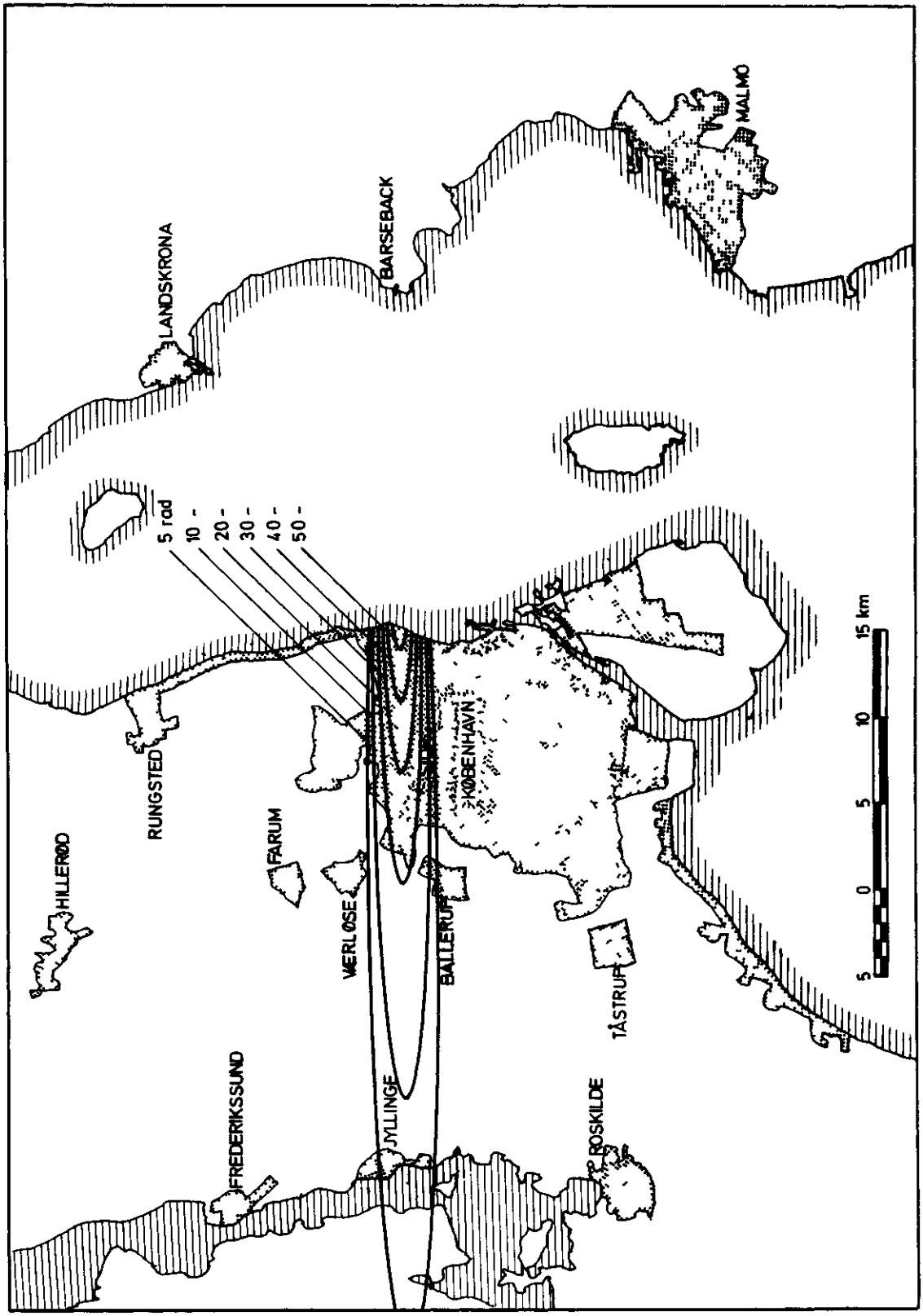


Figure26. Shielded bone marrow doses from a BWR1 accident 24hours after cloud passage
The meteorlogical conditions are Pasquill D, rain, wind speed 3m/s

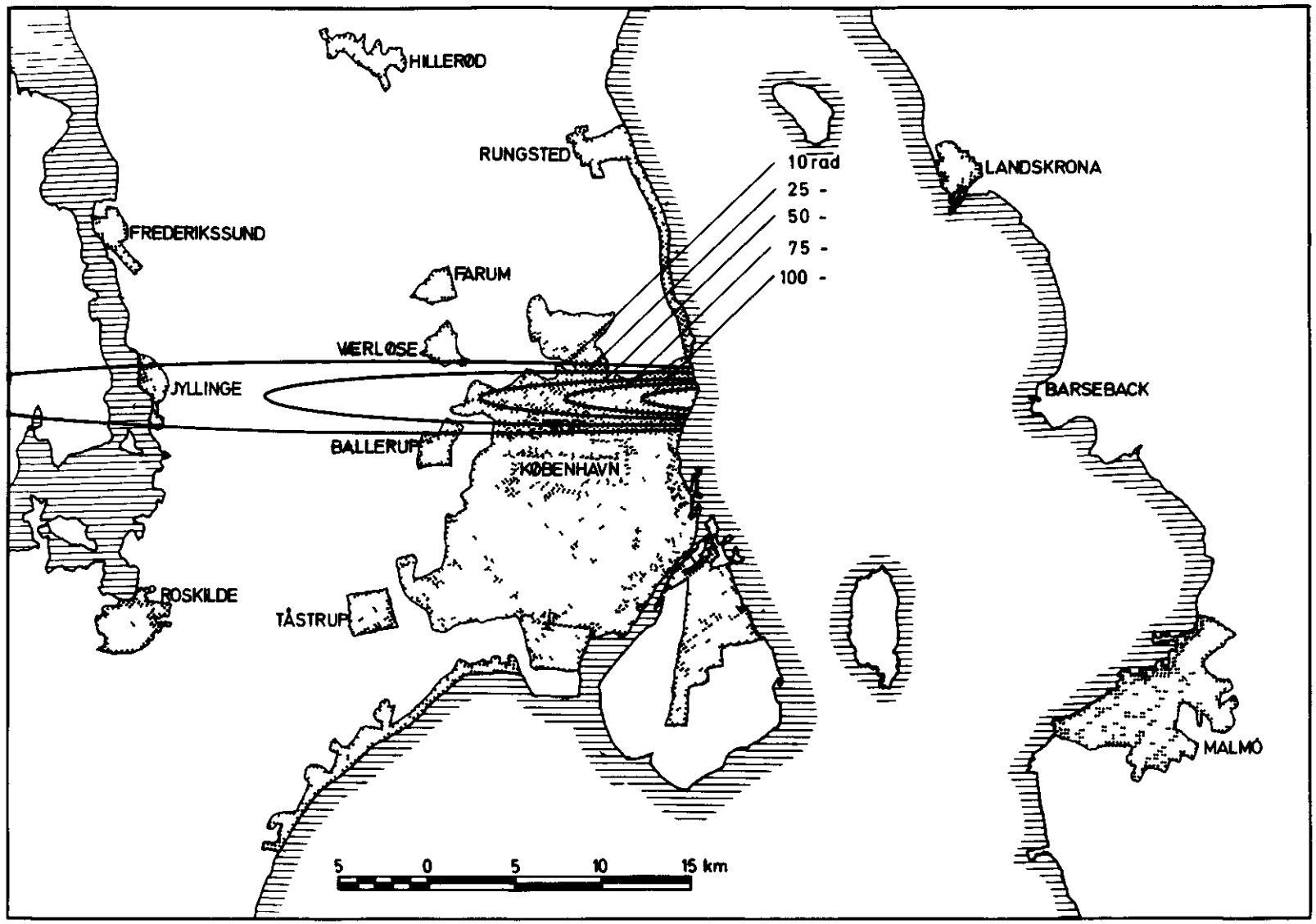


Figure27 Shielded bone marrow doses from a BWR1 accident 72hours after cloud passage
The meteorlogical conditions are Pasquill D, rain, wind speed 3m/s

One applies in the case of minimum medical treatment after irradiation and the other in the case of a so-called supportive treatment, which can include blood transfusion. According to fig. 15, the calculated bone marrow dose at a distance of 20 km from a BWR1 accident would be 57 rad. According to WASH-1400 such a dose, even assuming minimal medical treatment, would only give rise to ca. one fatality per 100 million persons irradiated.

The probability for acute fatalities as a result of the lung and GI tract doses is 0, according to WASH-1400, if doses to these organs are less than 2000 rad. For the thyroid, the corresponding limit is 25000 rad. Thus for the accidental releases in question, the bone marrow dose determines at what distance from the reactor acute fatalities may occur.

The number of latent injuries in the form of cancers and genetic effects not only depends on the acute doses, but also on the doses received throughout a longer period of time from the inhaled activity and the activity deposited on the ground. With respect to the latter activity, ^{137}Cs in particular is dominating.

An important conclusion of the present investigation is that bone marrow doses are dominated by gamma radiation from radioactive fallout on the ground. According to WASH-1400, gamma radiation from the ground can be shielded very effectively. A shielding factor of 0.2 is used in the present report corresponding to a brick-built single-family house or a moderate-size multi-story building, but shielding factors can be as low as 0.001 if the population is in cellars or very large multi-story buildings, such as office blocks. Residence inside buildings also reduces the dose from the passing cloud. As is the case in WASH-1400, the present report uses a shielding factor of 0.6. On the other hand, no reduction factor is used for the inhalation dose.

8.3. Discussion of the dose calculations

The doses calculated in this report must be considered to be larger than the doses that would really occur under the conditions in question. This is because of the following factors:

a) The radioactive releases are based on small-scale experiments with melts that have a large surface-to-volume ratio, which increases the release of radioactivity. A melted reactor core has a very much smaller surface-to-volume ratio, which would probably give rise to a significantly smaller release of activity.

b) Comparisons between the Barsebäck and the Peach Bottom reactors show that a coremelt accident at Barsebäck would probably give less relative release of activity to the atmosphere than a corresponding accident at Peach Bottom.

c) The calculations in the present report are based on the assumption that the weather situation does not alter during the course of the accident. Weather changes during the accident, e.g. in the form of a change in wind direction, would in general have a tendency to disperse the radioactive cloud, and thus to reduce the doses. Nevertheless, it is possible that weather changes could give rise to local increases in dose levels. In particular, intermittent rain could cause a large wash-out of radioactivity from the cloud in local areas at relatively large distances from the reactor, and this could result in large doses from radioactive fallout on the ground. The probability for large doses through this mechanism is, however, even less than the probabilities calculated in section 6.

d) In calculating doses from the radioactivity washed out from the plume during rainfall, it is assumed that all the washed-out activity remains on the ground. Because the bone marrow dose is dominated by radiation exposure from this activity, it is pessimistic to ignore the fact that some of the activity would be washed into drains or seep through the soil.

e) The method used for calculating the plume rise above ground as a result of its heat content ignores both the release of heat by the accompanying steam through condensation and the decay heat released as a result of radioactive decay in the cloud. This means that the height of the cloud above the ground is underestimated, which in the majority of cases means that the individual doses are overestimated.

f) The calculations of inhalation doses ignore the fact that these are reduced by residence inside buildings. There is no doubt that residence indoors, in particular if the premises are aired after the passage of the plume, would considerably reduce the inhalation doses.

If calculations of doses from accidental releases are to be made more realistic, there are two areas in particular where efforts would be worthwhile: 1) development of a more realistic atmospheric dispersion model describing the timevarying meteorological conditions, and 2) research relevant to a better understanding and determination of the magnitude, composition and probability of a hypothetical release of activity.

REFERENCES

1. S.Thykier-Nielsen. Modeller til beregning af eksterne gammadoser og inhalationsdoser fra frigørelser til atmosfæren af radioaktive stoffer. Risø-M-1725 (1974).

2. Reactor Safety Study. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. WASH-1400 (NUREG 75/1014).

3. Reactor Safety Study. Calculation of Reactor Accident Consequences. Appendix VI. WASH-1400.

4. F. Højerup, Fission Product Inventory in LWR's RP-4-76. Reactor Engineering Department, Risø.

5. J. Elkert el. al., BEGAFIP, et program for beräkning af klyvningsprodukternes aktivitet, beta-och gammaeffekter RF-72 374 (Studsvik).

6. D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates. National Air Pollution Control Association, Cincinatti, Ohio (1969). Public Health Service Publication No. 999-AP-26.

7. D.H. Slade (Editor), Meteorology and Atomic Energy (1968). TLD-24190.

8. Niels Otto Jensen, Occurrences of Stability Classes, Wind Speeds and Wind Directions as Observed at Risø. Risø-M-1666 (1973).

9. Recommendations of the International Commission on Radiological Protection. Report of Committee II on Permissible Dose for Internal Radiation. ICRP Publication 2, Pergamon Press, London (1959).

10. W.A.Lyons, Turbulent Diffusion and Pollutant Transport in Shoreline Environments. Lectures on Air Pollution and Environmental Impact Analysis. American Meteorological Society, Boston, 1975.

11. KFK-2195 (1975), Projekt Nukleare Sicherheit, 1. Halbjahresbericht 1975, page 365, fig. 4311-3.

APPENDIX 1

MODEL FOR CALCULATING DOSES FROM RADIOACTIVE MATERIAL RELEASED TO THE ATMOSPHERE (WASH-1400 MODEL)

by

Per Hedemann Jensen

1. ATMOSPHERIC DISPERSION MODEL

1.1. Gaussian dispersion model

If material is continuously released from a given point - e.g. a chimney stack or a reactor containment - it will disperse as a plume in the wind direction. To describe the concentration distribution in the plume, WASH-1400 uses the Gaussian dispersion model in which it is assumed that the concentration of material in the vertical direction in the plane perpendicular to the wind direction is Gaussian (normally) distributed with the standard deviation σ_z. In the horizontal direction perpendicular to the wind direction, a constant distribution is assumed with a horizontal extension of three standard deviations ($3\,\sigma_y$). The standard deviations, or dispersion parameters, σ_y and σ_z, are both functions of, e.g., the distance from the release point and the thermal stability of the atmosphere.

The concentration of material at the ground at a given distance from the release point is given by

$$\chi(x) = \sqrt{\frac{2}{\pi}} \cdot \frac{Q}{3 \cdot \sigma_y(x) \cdot \sigma_z(x) \cdot u} \cdot \exp\left(-\frac{z^2}{2\sigma_z(x)^2}\right) \qquad (1)$$

where

- $\chi(x)$ is the concentration at the ground at distance x, Ci/m^3
- Q is the release rate of a given isotope, Ci/s
- x is the distance from the release point in the wind direction, m
- u is the wind speed, m/s
- $\sigma_y(x)$ is the horizontal dispersion parameter, m
- $\sigma_z(x)$ is the vertical dispersion parameter, m
- z is the distance between the plume centreline and the ground, m.

WASH-1400 uses the dispersion parameters of Martin and Tikvart [2], which are largely identical to those of Turner [4].

If the release time is greater than half an hour, the plume is assumed to become wider because of fluctuations in the wind direction, at the same time as the concentration in the plume decreases. If the release time is termed τ ($\tau \geq 0.5$ hour), the concentration can be described by

$$\chi(x,\tau) = \sqrt{\frac{2}{\pi}} \cdot \frac{Q}{3 \cdot \sigma_y'(x,\tau) \cdot \sigma_z(x) \cdot u} \cdot \exp\left(-\frac{z^2}{2\sigma_z(x)^2}\right) \qquad (2)$$

where

$$\sigma_y'(x,\tau) = \sigma_y(x) \cdot \left(\frac{\tau}{0.5}\right)^{1/3} \qquad (3)$$

1.2. Correction for dry deposition

During transport in the wind direction some of the released activity will fall to the ground. The amount of activity which per time unit is deposited per area unit is proportional to the concentration at the ground and can be calculated from

$$q(x,\tau) = v_g \cdot \chi'(x,\tau) \qquad [Ci/m^2 s] \qquad (4)$$

where

v_g is the deposition velocity, m/s

$\chi'(x,\tau)$ is the air concentration at the ground, corrected for dry deposition, Ci/m^3.

The deposition velocity v_g is, inter alia, a function of particle size, surface roughness, wind speed and thermal stability. Its numerical value normally lies in the range 0.1-10 cm/s [2]. The deposition velocity for inactive gases is approximately equal to zero.

The correction factor for dry deposition is calculated as follows. The rate at which the activity is deposited on the

interval dx can be described by

$$\frac{dQ'}{dx} = -\int_{-1.5\sigma'_y}^{1.5\sigma'_y} v_g \chi'(x,\tau)\,dy \qquad [\text{Ci/m s}] \qquad (5)$$

$$= -\,3\cdot\sigma'_y\cdot v_g\cdot\chi'(x,\tau)$$

$$= -\sqrt{\frac{2}{\pi}}\cdot\frac{v_g}{u}\cdot\frac{\exp\left(-\frac{z^2}{2\sigma_z(x)^2}\right)}{\sigma_z(x)}\,Q'$$

With the initial condition $Q'(x=o)=Q_o$, the correction factor for dry deposition will be

$$\left(\frac{Q(x)}{Q_o}\right)_d = \exp\left(-\sqrt{\frac{2}{\pi}}\cdot\frac{v_g}{u}\cdot\int_o^x \frac{e^{-\frac{z^2}{2\sigma_z(x)^2}}}{\sigma_z(x)}\,dx\right) \qquad (6)$$

The corrected concentration at the ground will then be

$$\chi'(x,\tau) = \chi(x,\tau)\cdot\left(\frac{Q(x)}{Q_o}\right)_d \qquad (7)$$

Disregarding radioactive decay and other removal mechanisms on the ground during the release, the concentration of activity on the ground immediately after the passage of the whole plume will be

$$\psi(x,\tau) = v_g \cdot \chi'(x,\tau) \cdot \tau \qquad [\text{Ci/m}^2] \qquad (8)$$

1.3. Correction for wash-out during precipitation

If precipitation occurs during a release of activity, some of the activity will be washed out of the plume, and this wash-out takes place in all layers of the plume, provided that the height from where the precipitation falls is much greater than the height of the plume above ground.

The rate at which the activity is washed out on the interval dx is described by

$$\frac{dQ}{dx} = - \Lambda \frac{Q}{u} \qquad [\text{Ci/m s}] \qquad (9)$$

where Λ is the wash-out coefficient. This is, inter alia, a function of the type of precipitation and precipitation intensity, and its numerical value normally lies in the range 10^{-5} - 10^{-2} s^{-1} [2]. The wash-out coefficient for inactive gases is approximately equal to zero.

As $Q(x=o)=Q_o$, the correction factor for wash-out is

$$\left(\frac{Q(x)}{Q_o}\right)_w = \exp(-\Lambda \frac{x}{u}) \qquad (10)$$

The corrected activity concentration at the ground will then be

$$\chi'(x,\tau) = \chi(x,\tau) \cdot \left(\frac{Q(x)}{Q_o}\right)_w \qquad (11)$$

The amount of activity that, per time unit, is washed out on the ground is calculated from

$$q(x,\tau) = \int_0^{z_1} \Lambda\, \chi'(x,\tau)\,dz \qquad [\ Ci/m^2 s\ ] \qquad (12)$$

$$\simeq \int_0^{\infty} \Lambda\, \chi'(x,\tau)\,dz$$

where z_1 is the height from which the precipitation falls. Inserting (11) into (12), gives

$$q(x,\tau) = \int_0^{\infty} \Lambda \frac{\sqrt{\frac{2}{\pi}}\cdot Q\cdot \exp(-\Lambda\frac{x}{u})}{3\cdot\sigma_y'(x,\tau)\cdot\sigma_z(x)\cdot u} \exp\left(-\frac{z^2}{2\sigma_z(x)^2}\right) dz \qquad (13)$$

$$= \frac{\Lambda\cdot Q}{3\cdot u\cdot\sigma_y'(x,\tau)} \exp\ (-\Lambda\frac{x}{u}\ )$$

Disregarding radioactive decay and other removal mechanisms (also washing away and seepage as a result of rain during the release), the concentration of activity on the ground immediately after the passage of the whole plume will be

$$\psi(x,\tau) = \frac{\Lambda\cdot Q\cdot\tau}{3\cdot u\cdot\sigma_y'(x,\tau)} \exp(-\Lambda\frac{x}{u}\ ) \qquad [\ Ci/m^2] \qquad (14)$$

1.4. Correction for radioactive decay

After the release of a given isotope, this isotope will decay while being transported in the wind direction. The

part of the activity that has reached the distance x from the point of release will be reduced by the factor $\exp(-\lambda x/u)$, where λ is the decay constant of the isotope (1/s). The correction factor for radioactive decay will be

$$\left(\frac{Q(x)}{Q_o}\right)_r = \exp(-\lambda\frac{x}{u}) \qquad (15)$$

If the daughter product from the decay of the isotope in question is radioactive too, activity will gradually build-up en route and give rise to radiation doses. The build-up of the activity of the daughter product can be described by

$$Q_d(x) = Q\,\frac{\lambda_d}{\lambda_d-\lambda_m}\cdot(e^{-\lambda_m\frac{x}{u}} - e^{-\lambda_d\frac{x}{u}}) \qquad (16)$$

where

Q is the release rate of the isotope in question, Ci/s
$Q_d(x)$ is the activity of the daughter product at a distance x, Ci/s
λ_m is the decay constant for the released isotope, 1/s
λ_d is the decay constant for the daughter isotope, 1/s.

1.5. Thermal lift of the released activity

In an activity release associated with a core-melt accident, there will probably also be a release of considerable amounts of steam at a temperature of c. 100°C. Thus the plume can contain considerable thermal energy. The plume will therefore rise and reach a height determined by its heat content and by the atmospheric stability, by the wind speed and the height of the release. The distance between the plume centreline Z and the ground is calculated on the basis of Brigg's formula, and no attention is paid to the influence of latent and decay heat on the plume rise [2].

In cases of unstable or neutral atmosphere, Z is determined by

$$Z = h + (36 \cdot P)^{1/3} \cdot u^{-1} \cdot x^{2/3} \qquad (17)$$

where

h is the release height, m

P is the release rate of the heat content of the plume (less the latent heat), MW.

The plume rise is assumed to cease at a distance from the release point that is numerically equal to $177 \cdot P^{2/5}$. If this value is inserted into (17), the final height of the plume is found to be

$$Z = h + 104 \cdot P^{3/5} \cdot u^{-1} \qquad (18)$$

In cases of stable atmosphere, Z is determined by

$$Z = h + \left(\frac{215 \cdot P}{u \cdot s}\right)^{1/3} \qquad (19)$$

where the stability parameter s is given by

$$s = \frac{g}{T} \cdot \frac{\partial \theta}{\partial z} \qquad [1/s^2]$$

$\partial\theta/\partial z$ is here the potential temperature gradient for the atmosphere, g is the gravity acceleration, and T the temperature of the atmosphere [^{o}K].

1.6. Corrected air concentration

The corrected concentration at the ground of a given isotope released at the rate Q (Ci/s) will be, based on the above considerations,

$$\chi'(x,\tau) = \sqrt{\frac{2}{\pi}} \cdot \frac{Q}{3 \cdot \sigma_y'(x,\tau) \cdot \sigma_z(x) \cdot u} \cdot$$

$$\exp\left(-\left(\frac{z^2}{2\sigma_z(x)^2} + \sqrt{\frac{2}{\pi}} \cdot \frac{v_g}{u} \cdot \int_0^x \frac{e^{-\frac{z^2}{2\sigma_z(x)^2}}}{\sigma_z(x)}\, dx + \Lambda \frac{x}{u} + \lambda_m \frac{x}{u}\right)\right) \qquad (20)$$

Assuming that the mother product is also depositable, the concentration at the ground of a given daughter product built up en route will be

$$\chi'(x,\tau) = \sqrt{\frac{2}{\pi}} \cdot \frac{Q}{3 \cdot \sigma_y'(x,\tau) \cdot \sigma_z(x) \cdot u} \cdot \frac{\lambda_d}{\lambda_d - \lambda_m} \cdot \left(e^{-\lambda_m \frac{x}{u}} - e^{-\lambda_d \frac{x}{u}}\right) \cdot$$

$$\exp\left(-\left(\frac{z^2}{2\sigma_z(x)^2} + \sqrt{\frac{2}{\pi}} \cdot \frac{v_g}{u} \int_0^x \frac{e^{-\frac{z^2}{2\sigma_z(x)^2}}}{\sigma_z(x)}\, dx + \Lambda \frac{x}{u}\right)\right) \qquad (21)$$

In cases of dry weather, Λ is put equal to 0 in equations (20) and (21).

2. DOSE MODELS

2.1. Inhalation dose

A person located at a distance x from the release point, where the isotope concentration is $\chi'(x,\tau)$, will inhale activity at the rate $2.66 \cdot 10^{-4} \cdot \chi'(x,\tau)$ (Ci/s) using an breathing rate of

$2.66 \cdot 10^{-4}$ m^3/s [2]. If this person remains at this location during the whole passage of the plume, the total inhaled activity from the isotope in question is equal to $2.66 \cdot 10^{-4} \cdot \chi'(x,\tau) \cdot \tau$ (Ci).

After inhalation, the isotope will be distributed in the body organs, depending on the material and the chemical form in which it is found. The isotope will therefore deposit some of its radiation energy in these organs (lungs, thyroid gland, bone marrow, etc.). Gradually, as the isotope decays to a stable isotope (perhaps via one or more radioactive daughter products) and is biologically excreted from the body, the dose rate in the organ in question will decrease. The integrated dose over the time T from the inhaled isotope will be

$$D_{in}(x,\tau,T) = 2.66 \cdot 10^{-4} \cdot DF_{in}(T) \cdot \chi'(x,\tau) \cdot \tau \qquad [\text{rad}] \qquad (22)$$

where $DF_{in}(T)$ is the dose to a given organ per inhaled amount of activity (rad/Ci) integrated over T. If the release consists of N isotopes, the total inhalation dose to the organ in question for a person at location x during the whole passage of the plume is

$$D_{in}(x,\tau,T) = 2.66 \cdot 10^{-4} \cdot \tau \cdot \sum_{i=1}^{N} DF_{in_i}(T) \cdot \chi'_i(x,\tau) \qquad (23)$$

The dose conversion factors $DF_{in}(T)$ are given in WASH-1400 appendix VI, pages D-8 to D-12.

No reducation factor is used for people located inside buildings.

2.2. External gamma dose from the passage of the plume

During the passage of the plume of activity, at a given distance x, the dose rate originating from gamma radiation from the plume is constant. The gamma dose rate at this distance originates from the activity in the plume that is found within

a few hundred meters of the location. This is due to the relatively long range in air of gamma radiation. The dose rate can therefore be calculated as the sum of all dose rate contributions from the individual parts of the plume, when taking into account attenuation and build-up in the air layers between each plume element and the location. As this procedure requires a spatial integration of the concentration distribution over the volume of the plume for each of the photon energies of the isotopes, the approximation is made that the dose rate is first calculated in the centreline of the plume, as if the extent of the plume was infinite and had the same concentration as in the centreline, whereafter the dose rate is corrected for the finite extent and height above ground of the plume. The correction factor used is, thus, a function of both the dispersion parameter σ_z and the distance Z of the plume above the ground. It is tabled in WASH-1400, appendix VI, page 8-4 for different values of Z/σ_z and σ_z. Correction factors for values of σ_z and Z/σ_z not given in the table can be found by logarithmic interpolation.

The gamma dose to a given organ from a released isotope is calculated from

$$D_{plume}(x,\tau) = CF(\sigma_z(x), Z/\sigma_z(x)) \cdot DF_{plume} \cdot \tau \cdot \chi'(x,\tau) \cdot e^{\frac{Z^2}{2\sigma_z(x)^2}} \quad [rad] \qquad (24)$$

where

DF_{plume} is the gamma dose to a given organ per time-integrated concentration unit of the isotope in question, rad/Cis/m^3

$CF(\sigma_z(x), Z/\sigma_z(x))$ is the correction factor correcting the centreline dose rate in an infinite cloud to the dose rate at the ground from a cloud of finite extent.

The dose conversion factor DF_{plume} is given in appendix VI, table C-1, page C-5.

If the release consists of N isotopes, the total gamma

dose originating from residence at a distance x during the whole passage of the plume is obtained as

$$D_{plume}(x,\tau) = CF(\sigma_z(x),\ Z/\sigma_z(x)) \cdot \tau \cdot e^{\frac{Z^2}{2\sigma_z(x)^2}} \cdot \sum_{i=1}^{N} DF_{plume_i} \cdot \chi_i'(x,\tau) \qquad (25)$$

For residence inside buildings, a shielding factor is used that corrects for the absorbtion of some of the photon energy in the material of the building. WASH-1400, appendix VI, table 11-7, page 11-22 gives shielding factors for different types of buildings.

2.3. External gamma dose from deposited activity

During transport of the released activity in the wind direction, some of the activity will be eliminated from the lower layers of the plume and deposited on the ground. During precipitation, moreover, activity can be washed out from the whole plume height. When the activity is deposited on the ground, the gamma radiation it emits will give rise to a radiation dose to a person for the time that he/she remains in this location. The dose rate will gradually decrease as the individual isotopes decay to stable isotopes and are removed by seepage and washed away.

The activity concentration of a given isotope immediately after the passage of the plume at a distance x is given by, cf. sections 1.2 and 1.3 (decay on the ground during the release is disregarded):

dry weather:

$$\psi(x,\tau) = v_g \cdot \tau \cdot \chi'(x,\tau)$$

precipitation:

$$\psi(x,\tau) = v_g \cdot \tau \cdot \chi'(x,\tau) + \frac{\Lambda \cdot Q \cdot \tau}{3 \cdot \sigma_y'(x,\tau) \cdot u} \cdot \left(\frac{Q(x)}{Q_o}\right)_w \cdot \left(\frac{Q(x)}{Q_o}\right)_d \cdot \left(\frac{Q(x)}{Q_o}\right)_r$$

In calculating the dose rate it is assumed that this surface concentration is found infinitely far out to all sides around the point in question. If the factor DR_o indicates the dose rate from a given isotope to a given organ one meter above an infinite, plane-surfaced source of 1 Ci/m^2, the dose rate from this isotope at a distance x from the point of release, immediately after the passage of the plume, is obtained as

$$D'_o(x,\tau) = 0.7 \cdot DR_o \cdot \psi(x,\tau) \qquad [\text{rad/h}] \qquad (26)$$

The factor 0.7 takes into account the reduction of the radiation resulting from ground surface roughness. The dose rate will gradually decrease as the isotope is removed by decay and other mechanisms. The dose rate contribution from any daughter products resulting from decay is included in the total dose. The time variation of the dose rate can therefore in principle be described by

$$D'_{ground}(x,\tau,t) = 0.7 \cdot \psi(x,\tau) \cdot DR'(t) \qquad (27)$$

where DR'(t) now includes both the time function for any dose contribution from daughter products as well as the time function for the decline in activity, both with regard to radioactive decay and to other mechanisms, e.g. seepage and washing away with rainwater.

The integrated dose over the time T from the isotope in question is calculated from

$$D_{ground}(x,\tau,T) = 0.7 \cdot \psi(x,\tau) \cdot \int_o^T DR'(t)dt \qquad [\text{rad}] \qquad (28)$$

$$= 0.7 \cdot \psi(x,\tau) \cdot DF_{ground}(T)$$

The dose conversion factor $DF_{ground}(T)$ is given in WASH-1400, appendix VI, table C-2, page C-6, for T = 1 day and T = 7 days.

The total dose from a release of N isotopes is calculated from

$$D_{ground}(x,\tau,T) = 0.7 \cdot \sum_{i=1}^{N} \psi_i(x,\tau) \cdot DF_{ground_i}(T) \qquad (29)$$

For people inside buildings, use is made of a shielding factor that depends on the type of building. Appendix VI, table 11-9, page 11-25, give shielding factors for different types of buildings.

3. TEST CALCULATIONS WITH THE WASH-1400 MODEL

On the basis of the computer program RASDOS 1, a number of test calculations were made of the bone marrow doses, lung doses, GI-tract doses and thyroid gland doses as a function of distance from the release point. Figure VI 13-6, in appendix VI of WASH-1400 was used for comparison.

Figure VI 13-6 shows the doses as function of distance from the reactor in the wind direction from a large, cold release from a 3200 MWt BWR during stable weather conditions (Pasquill F, wind speed 2 m/s). The release per cents for the individual isotopes in this accident were obtained from the authors of WASH-1400. The release- and cooling-times are, respectively, 3 and 3.5 h, and the release is assumed to take place at ground level. Constant meteorological conditions are assumed during the release. The doses shown on figure VI 13-6 are given without shielding reduction for residence inside buildings, but use is made of a reduction factor of 0.7 for the external gamma dose from deposited activity because of the rougnness of the ground surface.

With the above release conditions and the same time integration intervals as given on figure VI 13-6, the doses from this accident are calculated, and the calculated organ doses are

shown on figures I-1 to I-4. The agreement observed must be considered satisfactory.

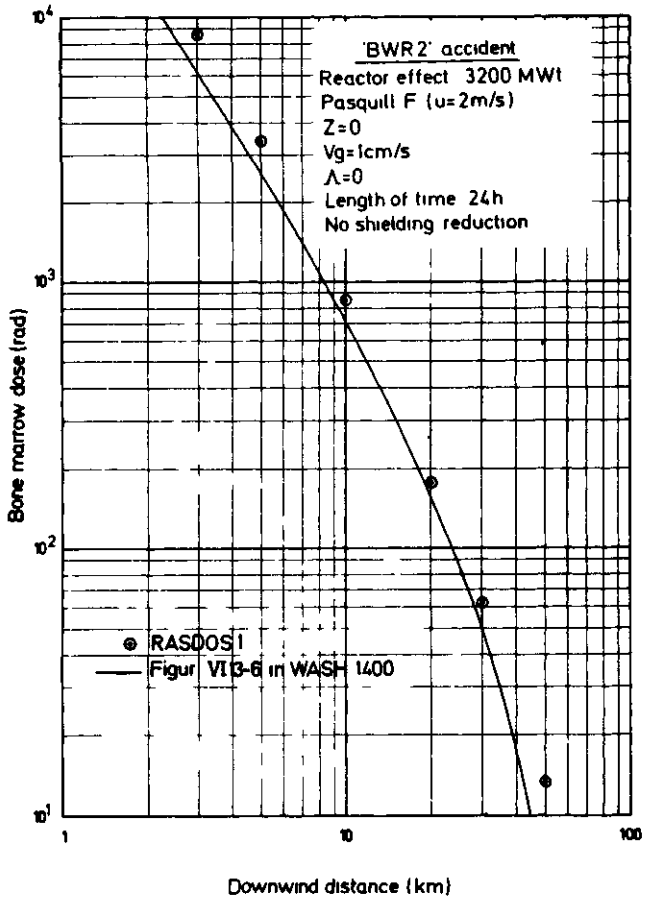


Figure I-1. Bone marrow dose from "BWR2" accident

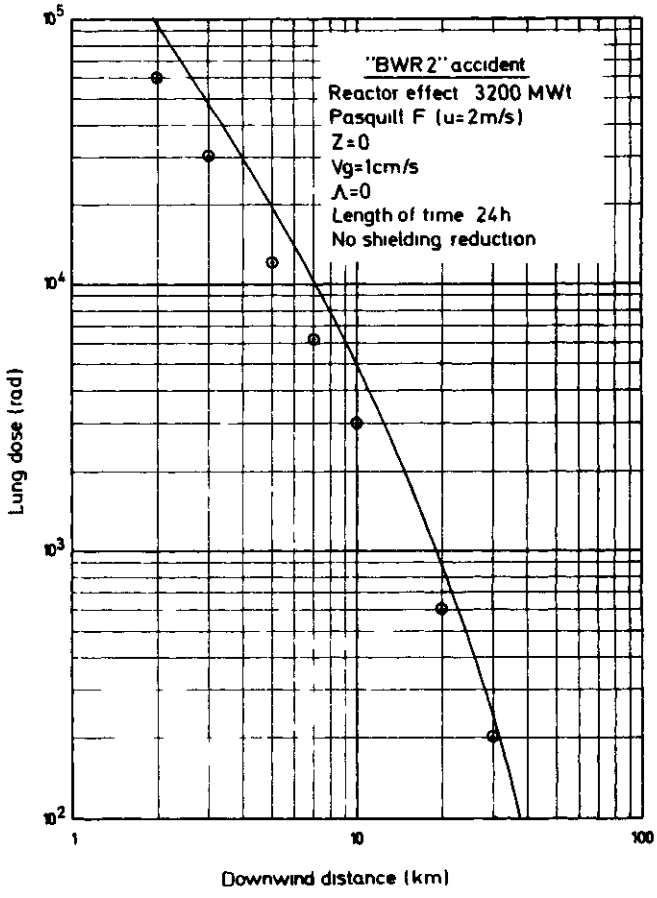


Figure I-2. Lung dose from "BWR 2" accident

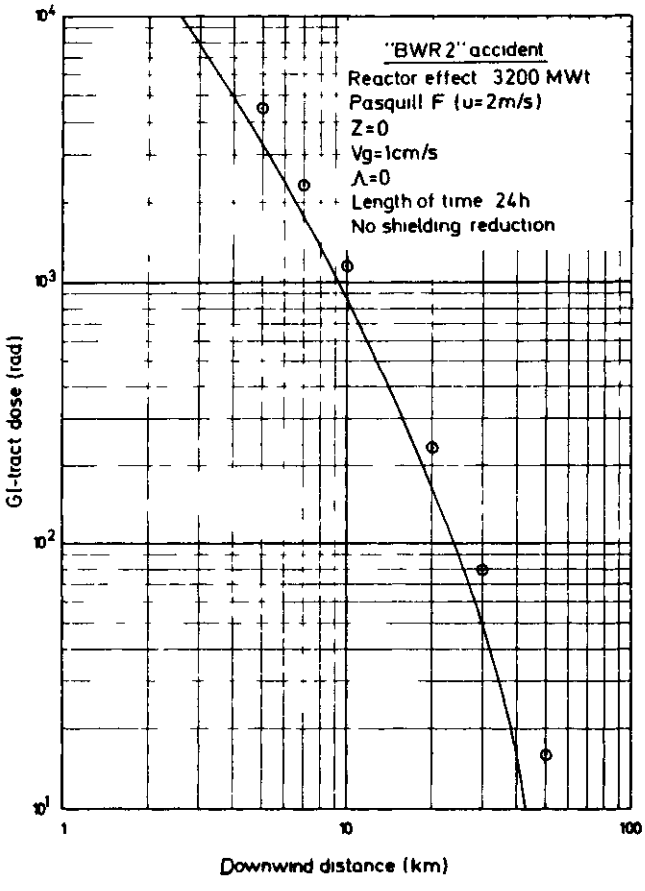


Figure I-3. GI-tract dose from "BWR 2" accident

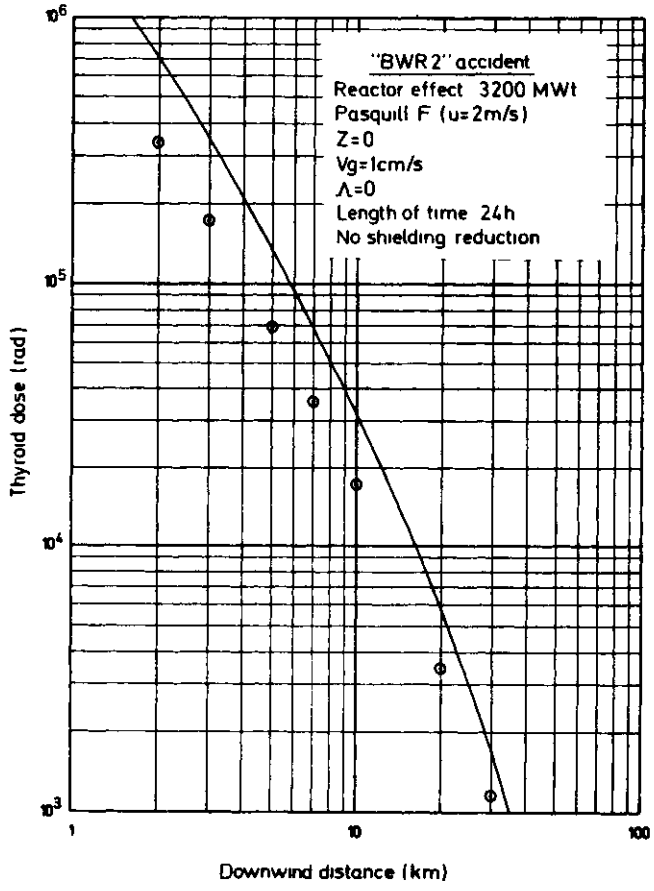


Figure I-4. Thyroid dose from "BWR 2" accident

3. REFERENCES

1. Reactor Safety Study. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. WASH-1400 (NUREG 75/014). USNRC (1975).

2. Reactor Safety Study. Calculation of Accident Consequences. Appendix VI. WASH-1400.

3. S. Thykier-Nielsen, Modeller til beregning af eksterne gammadoser og inhalationsdoser fra frigørelser til atmosfæren af radioaktive stoffer. Risø-M-1725 (1974).

4. D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates. National Air Pollution Control Association, Cincinatti, Ohio (1969). Public Health Service Publication No. 999-AP-26.

APPENDIX 2

MODEL FOR CALCULATING DOSES FROM RADIOACTIVE MATERIAL RELEASED TO THE ATMOSPHERE (RISØ MODEL)

by

Søren Thykier-Nielsen

1. DISPERSION MODEL

1.1. General description

The Gaussian model is used as basis [1, 2 and 4]. According to this model, a Gaussian distribution is assumed for the material concentration in the plane perpendicular to the wind direction. If it is further assumed that the ground surface has total reflection, the diffusion formula will be in a rectangular co-ordinate system with the origin in the source point (point of release) and the x-axis in the wind direction:

$$X(x,y,z,s,u) = Q(x,t) \cdot Sg(x,y,z,s,u) \qquad (1)$$

where

$$Sg(x,y,z,s,u) = \frac{1}{2 \cdot \pi \cdot u \cdot \sigma_y(x,s) \cdot \sigma_z(x,s)} \cdot e^{-\frac{y^2}{2 \cdot \sigma_y(x,s)^2}} \cdot \left[e^{-\frac{z^2}{2 \cdot \sigma_z(x,s)^2}} + e^{-\frac{(z+2 \cdot H)^2}{2 \cdot \sigma_z(x,s)^2}} \right] \qquad (2)$$

where

$X(x,y,z,s,u)$	=	concentration [Ci/m^3]
$Sg(x,y,z,s,u)$	=	relative concentration [s/m^3]
(x,y,z)	=	co-ordinates of the detector point [m]
s	=	atmospheric stability category
u	=	wind speed [m/s]
$\sigma_y(x,s)$	=	horizontal dispersion parameter [m]
$\sigma_z(x,s)$	=	vertical dispersion parameter [m]
$Q(x,t)$	=	effective source term [Ci/s] at time t
H	=	effective stack height [m]

In eq. 2 it is assumed that the diffusion in the x-direction can be ignored. This assumption applies when the release takes place over a period of time that is equal to or greater than the transport time ($\frac{x}{u}$) from the source to the detector point in question [2 and 4].

Equation 2 cannot be used in cases where dispersion conditions are peceptibly influenced by a mixing layer that sets an upper limit to the atmospheric layer in which the released material is dispersed and in which there occurs turbulent diffusion. The existence of such a mixing layer will imply that the vertical distribution of material will change from a Gaussian to a homogeneous distribution with increasing distance from the source. As the mixing layer is supposed to be totally reflecting, the relative concentration distribution can be calculated, according to Turner [6], as follows:

The distribution of material below the mixing layer is influenced first from the distance x_L, where the concentration at the lower limit of the mixing layer is equal to one-tenth of the concentration in the plume centreline. From the distance x_L there is a gradual transition between a Gaussian and a homogeneous distribution in the vertical plane. The material distribution can, for $x_L < x$, be calculated by "folding" the actual source, both in relation to the ground surface and to lower limit of the mixing layer. In other words, there is a superposition of a number of imaginary sources (in principle infinitely many) that are identical to the actual source but lying at different distances under the ground surface, or above the lower limit of the mixing layer, respectively.

From a certain distance x_C ($x_L < x_C$), the vertical material distribution may be considered as homogeneous with good approximation.

x_L is calculated from

$$\sigma_z(x_L) = \frac{L-H}{\sqrt{2 \cdot \ln(10)}} = 0.466 \cdot (L-H) \qquad [\text{meter}]$$

where

L = the mixing height (the height of the atmospheric layer in which the released material is dispersed) [meter]

H = effective stack height [meter]

x_C is calculated from

$$\sigma_z(x_C) = \sigma_{zL} = \sqrt{\frac{2}{\pi}} \cdot L = 0.798 \cdot L$$

Thus there are the following expressions for the relative concentration:

a. $0 < x < x_L$

$$(2)\quad Sg(x,y,z,s,u) = \frac{\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)}{2\cdot\pi\cdot\sigma_y(x,s)\cdot\sigma_z(x,s)\cdot u}\cdot$$

$$\left[\exp-\left(\frac{z^2}{2\cdot\sigma_z(x,s)^2}\right)+\exp\left(-\frac{(z+2\cdot H)^2}{2\cdot\sigma_z(x,s)^2}\right)\right]$$

b. $x_L \leq x \leq x_C$

$$(3)\quad Sg_{B1}(x,y,z,s,u) = \frac{\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)}{2\cdot\pi\cdot\sigma_y(x,s)\cdot\sigma_z(x,s)\cdot u}\cdot$$

$$\left\{\exp\left(-\frac{z^2}{2\cdot\sigma_z(x,s)^2}\right)+\exp\left(-\frac{(z+2\cdot H)^2}{2\cdot\sigma_z(x,s)^2}\right)+\right.$$

$$\sum_{i=1}^{4}\left[\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L-2\cdot H-z}{\sigma_z(x,s)}\right)^2\right)+\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L-z}{\sigma_z(x,s)}\right)^2\right)\right.$$

$$\left.\left.+\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L+z}{\sigma_z(x,s)}\right)^2\right)+\exp\left(-\frac{1}{2}\cdot\left(\frac{2\cdot i\cdot L+2\cdot H+z}{\sigma_z(x,s)}\right)^2\right)\right]\right\}$$

c. $x_C \leq x$

$$(4)\quad Sg_{B2}(x,y,z,s,u) = \frac{\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)}{\pi\cdot\sigma_y(x,s)\cdot\sigma_{zL}\cdot u}$$

The equations under b and c only apply to $-H \leq z < H$.

1.2. Mean concentrations

The mean concentration, $Sgm(x,z,s,u,\alpha)$, for a (narrow) sector is at a given distance, x, from the release point [4]:

$$(5)\quad Sgm(x,z,s,u,\alpha) = \sqrt{\frac{\pi}{2}} \cdot \frac{\sigma_y(x,s)}{2\cdot x\cdot tg(\alpha)} \cdot \left[erf\left(\frac{x\cdot tg(\alpha)}{\sqrt{2}\cdot\sigma_y(x,s)}\right) - erf\left(-\frac{x\cdot tg(\alpha)}{\sqrt{2}\cdot\sigma_y(x,s)}\right)\right]\cdot Sg(x,o,z,s,u)$$

where

$erf(t) = \int_o^t \frac{2}{\sqrt{\pi}} \cdot e^{-v^2}\, dv$, the error function

α = the half sector angle for the sector in question

$2\cdot x\cdot tg\alpha$ = the sector width.

With good approximation, eq. (5) can be used for sectors with an angle of 30^o or less.

Another, and from a meteorological point of view principally different way of calculating the mean concentration in a given sector is to use the crosswind-integrated concentration:

$$Sg_t(x,z,s,u) = \int_{-\infty}^{+\infty} Sg(x,y,z,s,u)\, dy$$

$$= \sqrt{2\pi}\cdot\sigma_y(x,s)\cdot Sg(x,o,z,s,u)$$

The mean concentration, $Sgm_t(x,z,s,u,\alpha)$ at a given distance, x, will then be for a sector of width $2\cdot\alpha$ degrees:

$$(6)\quad Sgm_t(x,z,s,u,\alpha) = \frac{\sqrt{2\cdot\pi}\cdot\sigma_y(x,s)}{\frac{\alpha}{180}\cdot 2\cdot\pi\cdot x}\cdot Sg(x,o,z,s,u)$$

$$= \sqrt{\frac{2}{\pi}}\cdot\frac{90\cdot\sigma_y(x,s)}{\alpha\cdot x}\cdot Sg(x,o,z,s,u)$$

It can be shown that

$Sgm(x,z,s,u,\alpha) < Sgm_t(x,z,s,u,\alpha)$ for all $\alpha > 0$.

For given x-values, the difference between Sgm and Sgm_t will be less the smaller σ_y is in relation to the half sector-width,

i.e.,

$$\frac{\sigma_y(x,s)}{x \cdot tg\alpha} \to 0 \Rightarrow \frac{Sgm(x,z,s,u,\alpha)}{Sgm_t(x,z,s,u,\alpha)} \to 1$$

1.3. Effective stack height

When the release point is in the open country, the height at which the dispersion of the released material starts is generally greater than the actual height of the release point above ground. The difference is mainly due to turbulence around the point from which the material is released and to the speed at which the material travels upwards. Further, the temperature of the released material is of significance, because the plume (or cloud) will rise to a height that depends partly on the relationship between the emission of heat and the heat received from the surrounding air, and partly on atmospheric stability and wind speed. If the plume (or cloud) contains radioactive material, then heat will be continuously produced in the plume (cloud). This "self-heating" can in certain cases become so large that the plume continues to rise for a very long period of time, with the result that the effective stack height increases at the same time as the plume (cloud) moves in the direction of the wind. In the dispersion equations mentioned here, the effective stack height H (a constant) must be replaced by the function H(x), which is a function of the distance in the wind direction, x. The problem is dealt with in greater detail in [12] and [3].

1.4. The effective source term

The effective source term, Q(x,t), is equal to the release rate corrected for changes taking place in the distance between source point and detector point (as a result of fallout, radioactive decay, etc).

If a radioactive isotope is released with a constant speed ε [Ci/s], then the effective source term will be:

$$(7) \quad Q(x,t) = \varepsilon \cdot e^{-\lambda \cdot \frac{x}{u}} \text{ [Ci/sek] for } tf_1 + \frac{x}{u} \leq t \leq tf_2 + \frac{x}{u}$$

$$= 0 \quad \text{for } t < tf_1 + \frac{x}{u} \text{ V } tf_2 + \frac{x}{u} < t$$

where

tf_1 = the time at which the release started
tf_2 = the time at which the release stopped
λ = the decay constant

The decay of the released isotopes during transport in the wind direction away from the place of release implies the creation of daughter products. Considering a situation where an isotope, the mother product, and its radioactive daughter product are both released from the source with the constant speeds ε_p [Ci/s], respectively, ε_d [Ci/s], the effective source terms will then be:

for the mother product:

$$Q_p(x,t) = \varepsilon_p \cdot e^{-\lambda_p \frac{x}{u}} \text{ [Ci/sek]}$$

for the daughter product

$$Q_d(x,t) = \varepsilon_d \cdot e^{-\lambda_d \frac{x}{u}} + \frac{\varepsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p} \cdot \left(e^{-\lambda_p \frac{x}{u}} - e^{-\lambda_d \frac{x}{u}} \right) \text{ [Ci/sek]}$$

where

λ_p = the decay constant for the mother product [s^{-1}]
λ_d = the decay constant for the daughter product [s^{-1}]

Note that ε_d may perhaps be equal to 0 (i.e. no separate release of the daughter product).

In calculating doses, the concept <u>time-integrated source term</u> is used:

$$I(x,te_1,te_2) \equiv \int_{te_1}^{te_2} Q(x,\tau)\, d\tau$$

For a release with constant speed, such as described above, one finds:

$$(8)\quad I(x,te_1,te_2) =$$

$$(\min(te_1, tf_2 + \tfrac{x}{u}) - \max(te_1, tf_1 + \tfrac{x}{u})) \cdot Q(x,t)$$

$$\text{for } te_1 \leq tf_2 + \tfrac{x}{u} \wedge tf_1 + \tfrac{x}{u} \leq te_2, \text{ og}$$

$$= 0 \text{ for } tf_2 + \tfrac{x}{u} < te_1 \vee te_2 < tf_1 + \tfrac{x}{u}$$

1.5. Deposition

1.5.1. Deposition in general

Some of the material in the plume may deposit on the ground during transport in the wind direction. The mechanism of deposition is rather complicated, and here are only given the methods for calculating dry deposition and washout that are connected with the Gaussian model. Reference should otherwise be made to [6, 7 and 1].

When considering dry deposition, the so-called velocity of deposition, v_g, is used. This is defined as:

$$v_g = \frac{\text{deposited material per unit area of ground}}{\text{time integrated plume concentration at ground level}}$$

The amount of material that per time unit is deposited per area unit of the ground surface, is calculated as:

$$(9)\quad w_D(x,y,s,u) = v_g \cdot \chi'(x,y,-H,s,u) \quad [Ci/m^2/s]$$

where

v_g = velocity of deposition [m/s]

$\chi'(x,y,-H,s,u) = Q_D(x,t,s) \cdot Sg(x,y,-H,s,u)$

material concentration at ground level [Ci/m^3] corrected for deposition

Q_D (x,t,s) = effective source term corrected for deposition [Ci/s].

Assuming that deposition takes place along the whole distance from source point to detector point, $Q_D(x,t,s)$ is calculated as

$$(10)\quad Q_D(x,t,s) = Q_o \cdot \exp\left[-\lambda \cdot \frac{x}{u} - \int_o^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp\left[-\frac{1}{2}\cdot\left[\frac{H}{\sigma_z}\right]^2\right]}{\sigma_z(x,s)}\, dx\right]$$

where Q_o is the effective source term at the point of release. Wash-out is described by the so-called wash-out coefficient, l_g, defined as:

$$l_g = \frac{\text{fraction of total amount of activity washed out}}{\text{duration of precipitation}}$$

= the relative change of the amount of activity per time unit.

The amount of material that is deposited per area unit of the ground surface per time unit is calculated as

$$(11)\quad W_N(x,y,s,u) = \frac{Q_N(x,t,s)\cdot l_g}{\sqrt{2\cdot\pi}\cdot u\cdot\sigma_y(x,s)} \cdot \exp\left[-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right] [Ci/m^2/sek]$$

where

l_g = the wash-out coefficient [s^{-1}]

$Q_N(x,t,s) = Q_o(t) \cdot e^{-(l_g + \lambda)\cdot\frac{x}{u}}$ [Ci/s]

= effective source term corrected for wash-out

$Q_o(t)$ = effective source term [Ci/s] at the point of release.

When dealing with mean concentrations at given distances (see section 1.2), the factor

$$\exp\left[-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right], \quad \text{in formula 11}$$

is replaced either by

$$\sqrt{\frac{\pi}{2}} \cdot \frac{\sigma_y(x,s)}{2 \cdot x \cdot tg(\alpha)} \cdot \left[erf\left(\frac{x \cdot tg(\alpha)}{\sqrt{2} \cdot \sigma_y(x,s)} \right) - erf\left(- \frac{x \cdot tg(\alpha)}{\sqrt{2} \cdot \sigma_y(x,s)} \right) \right]$$

or by

$$\sqrt{\frac{\pi}{2}} \cdot \frac{90 \cdot \sigma_y(x,s)}{\alpha \cdot x}$$

The material concentration in the plume, corrected for wash-out will be:

$$\chi_N(x,y,z,s,u) = Q_N(x,t,s) \cdot Sg(x,y,z,s,u)$$

During precipitation, dry and wet deposition (wash-out) can occur simultaneously. Assuming that the two deposition mechanisms influence the material in the cloud (or plume) independently of each other, the source term $Q_{DN}(x,t,s)$ corrected for deposition can be calculated as:

$$(12)\quad Q_{DN}(x,t,s) = Q_o(t) \cdot \exp\left(-(\lambda + 1_g) \cdot \frac{x}{u} - \int_o^x \frac{v_g}{u} \sqrt{\frac{2}{\pi}} \frac{\exp(-\frac{1}{2} \cdot (\frac{H}{\sigma_z})^2)}{\sigma_z(x,s)} dx \right)$$

The amount of material that per time unit is deposited per area unit of the ground surface will be:

$$(13)\quad W_{DN}(s,y,s,u) = v_g \cdot Q_{DN}(x,t,s) \cdot Sg(x,y,-H,s,u) + \frac{Q_{DN}(x,t,s) \cdot 1_g}{\sqrt{2} \cdot \pi \cdot u \cdot \sigma_y(x,s)} \cdot \exp\left(\frac{-y^2}{2 \cdot \sigma_y(x,s)^2} \right) \quad [Ci/m^2/sek]$$

Both for dry deposition and for wash-out it applies that, provided the deposited amount of material is not removed from the location where it is deposited in any other way than by

radioactive decay, the total deposited amount at a given time, t, will be:

$$(14)\quad W(x,y,s,u,t,td_1,td_2) = \int_{td_1}^{t} w(x,y,s,u)\,dt$$

$$= 0 \quad \text{for } t \leq td_1$$

$$= w(x,y,s,u) \cdot \frac{1}{\lambda} \cdot \left(1-e^{-\lambda\cdot(t-td_1)}\right) \quad \text{for } td_1 < t \leq td_2$$

$$= w(x,y,s,u) \cdot \frac{1}{\lambda} \cdot \left(1-e^{-\lambda\cdot(td_2-td_1)}\right)\cdot e^{-\lambda\cdot(t-td_2)} \quad \text{for } td_2 < t$$

where

td_1 = time at which deposition started
td_2 = time at which deposition stopped.

It is assumed that the dispersion conditions and deposition parameters (v_g and 1_g) do not change in the period of time in question.

Should there be a mixing layer above the release area, this will influence the dispersion conditions and thus possibly also the deposition. Formulas (9) to (14) will thus not necessarily apply in such a case.

1.5.2. Deposition of daughter products

Consider the situation mentioned in section 1.4, where an isotope - the mother product - and its radioactive daughter product are both released from the source with the constant rates ε_p [Ci/s] and ε_d [Ci/s], respectively. When calculating the source term for the daughter product corrected for deposition, as well as the amount of the daughter product deposited on the ground, one must take into account whether the mother product is deposited on the ground or not.

The source term of the daughter product corrected for deposition will be:

a. Without deposition of the mother product:

$$(15)\quad Q_d^*(x,s) = \varepsilon_d \cdot \exp(-\lambda_d \cdot \frac{x}{u}) \cdot g(x,s) + \frac{\varepsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p + \ell} \cdot (\exp(-\lambda_p \frac{x}{u}) - \exp(-\lambda_d \cdot \frac{x}{u}) \cdot g(x,s))$$

b. With deposition of the mother product

$$(16)\quad Q_d^*(x,s) = (\varepsilon_d \cdot \exp(-\lambda_d \cdot \frac{x}{u}) + \frac{\varepsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p} (\exp(-\lambda_p \cdot \frac{x}{u}) - \exp(-\lambda_d \cdot \frac{x}{u}))) \cdot g(x,s)$$

where

$$\ell = l_t = \left(+ \int_o^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} \cdot (\frac{H}{\sigma_z(x,s)})^2)}{\sigma_z(x,s)} dx \right) \cdot \frac{u}{x}$$ for dry deposition

$$= l_g$$ for våddeponering

$$= l_g + \frac{u}{x} \cdot \int_o^x \frac{v_g}{u} \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} (\frac{H}{\sigma_z(x,s)})^2)}{\sigma_z(x,s)} dx$$ for simultaneous dry and wet deposition

$$g(x,s) = \exp\left(- \int_o^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} (\frac{H}{\sigma_z(x,s)})^2}{\sigma_z(x,s)} dx \right)$$ for dry deposition

$$= \exp(-l_g \cdot \frac{x}{u})$$ for våddeponering

$$= \exp\left(- \left(l_g \cdot \frac{x}{u} + \int_o^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp(-\frac{1}{2} (\frac{H}{\sigma_z(x,s)})^2}{\sigma_z(x,s)} dx \right) \right)$$ for simultaneous dry and wet deposition

The other symbols as given earlier.

It is assumed that the same deposition parameters can be used for both the mother product and the daughter product.

To facilitate the solution of the differential equations used in deriving the expression for the source term of the daughter product in dry deposition, the function $g(x,s)$ is approximated by the expression $\exp(-l_t \cdot \frac{x}{u})$. This approximation, which is only used in calculating the amount of the daughter product created by the decay of the mother product during transport from the source to the point in question, results in

a small over-estimation of both the source term $Q_d^*(x,s)$ and the amount of daughter product deposited on the ground.

The amount of material deposited per area unit of the ground per time unit is found by replacing Q_D, Q_N or Q_{DN} in formulas (9), (11) and (13) by the relevant expression for Q_d^*.

The total amount deposited of the daughter product at a given location is, at a given time, t:

$$(17)\quad W_d(x,y,s,u,t) = \int_{td_1}^{t} w_d(x,y,s,u)\,dt$$

If the mother product is not deposited, the expressions for W_d will be like those for W, i.e. the expressions given under formula (14). The following expressions therefore only apply to those cases where both mother and daughter product are deposited:

$$(18)\quad W_d(x,y,s,u,t,td_1,td_2) = 0 \quad \text{for } t \leq td_1$$

$$= w_d(x,y,s,u)\cdot\frac{1}{\lambda_d}(1-\exp(-\lambda_d\cdot(t-td_1))$$

$$+ w_p(x,y,s,u)\cdot\left(\frac{1}{\lambda_p} + \frac{1}{\lambda_d-\lambda_p}\cdot(\exp(-\lambda_d\cdot(t-td_1))\right.$$

$$\left. - \frac{\lambda_d}{\lambda_p}\cdot\exp(-\lambda_p\cdot(t-td_1))\right) \qquad \text{for } td_1 < t \leq td_2$$

$$= w_d(x,y,s,u)\cdot\frac{1}{\lambda_d}\,(1-\exp(-\lambda_d\cdot(td_2-td_1))\cdot\exp(-\lambda_d\cdot(t-td_2))$$

$$+ w_p(x,y,s,u)\cdot\frac{1}{\lambda_d-\lambda_p}\cdot\left(\frac{\lambda_d}{\lambda_p}\cdot(1-\exp(-\lambda_p\cdot(td_2-td_1)))\cdot\exp(-\lambda_p\cdot(t-td_2))\right.$$

$$\left. -(1-\exp(-\lambda_d\cdot(td_2-td_1)))\cdot\exp(-\lambda_d\cdot(t-td_2))\right) \qquad \text{for } td_2 < t$$

The index d indicates the daughter product and index p the mother product.

2. CALCULATION OF DOSES

2.1. Inhalation doses

A person located at a given time at a given point, P(x,y,z), will inhale radioactive material at a rate that is equal to the product of the breathing rate and the concentration of the radioactive material at this point.

The resulting dose (in rem) to a given organ (lungs, thyroid gland, etc.) is calculated as:

$$(19)\quad D_I(x,y,z,s,u) = \beta \cdot S(x,y,z,s,u) \cdot \sum_{i=1}^{n_{iso}} \delta_{k,i}(d) \cdot I_i(x,te_1,te_2)$$

where

β	= breathing rate [m^3/s]
$S(s,y,z,s,u)$	= relative concentration [s/m^3]
s	= stability category
u	= wind speed [m/s]
$\delta_{k,i}(d)$	= dose to organ k per inhaled unit of radioactivity of isotope no. i, integrated from the time at which the plume passed point P until d days after this time [rem/Ci]
$I_i(x,te_1,te_2)$	= integrated source term [Ci]
te_1	= time when exposure started [s]
te_2	= time when exposure ceased [s]
n_{iso}	= total number of isotopes in the plume.

2.2. External gamma doses

The external gamma doses to a person at a given point $P(x_d,y_d,z_d)$ is obtained by integrating the radiation contributions from the individual elements of the plume. If the plume contains n_{iso} isotopes, whose photon energies are distributed over n_e energy groups, the gamma dose (in rem) at point P is found to be:

$$(20)\quad D_G(x_d,y_d,z_d,s,u) = \frac{K}{4\pi} \cdot \sum_{k=1}^{n_e} E_k^{\gamma} \cdot \sigma_k^{\gamma} \cdot \sum_{i=1}^{n_{iso}} f_{k,i} \cdot$$

$$\int_{\max(o,u\cdot(te_1-tf_2))}^{u\cdot(te_2-tf_1)} \frac{I_i(x,te_1,te_2)}{2\cdot\pi\cdot\sigma_y(x,s)\cdot\sigma_z(x,s)\cdot u} \cdot$$

$$\left\{\int_{-H}^{\infty} \left(\exp\left(-\frac{z^2}{2\cdot\sigma_z(x,s)^2}\right)+\exp\left(-\frac{(z+2\cdot H)^2}{2\cdot\sigma_z(x,s)^2}\right)\right)\cdot\right.$$

$$\left.\left(\int_{-\infty}^{+\infty} \frac{B(\mu_k\cdot r)\cdot e^{-\mu_k\cdot r}}{r^2} \cdot\exp\left(-\frac{y^2}{2\cdot\sigma_y(x,s)^2}\right)dy\right)dz\right\} dx$$

where

r^2	$= (x-x_d)^2+(y-y_d)^2+(z-z_d)^2$ [m^2]
s	= stability category
tf_1	= time for start of release [s]
tf_2	= time for end of release [s]
te_1	= time for start of exposure [s]
te_2	= time for end of exposure [s]
K	= conversion factor, dose rate/(absorbed energy per gram per Ci) [(rem/s)/(MeV/g/Ci].
n_e	= number of energy groups
K_k^γ	= mean photon energy in k'th energy group [MeV]
$\sigma_k^\gamma=\sigma_k^\gamma(E_k^\gamma)$	= energy absorption coefficient for air in k'th energy group [m^2/g]
$f_{k,i}$	= photon yield of isotope no. i in the k'th energy group
$\mu_k = \mu(E_k)$	= linear attenuation coefficient for air, in the k'th energy group [m^{-1}]
$B(\mu_k\cdot r)$	$= 1 + K_E(E_k)\cdot\mu_k\cdot r$, the build-up factor for the k'th energy group
$I_i(x,te_1,te_2)$	= integrated source term for isotope no. i [Ci]

The creation of daughter products (see sec. 1.4) and the deposition (see sec. 1.5) may be accounted for in the integrated source term.

The model for external gamma doses from a plume does not take any possible mixing layer into consideration.

2.3. External gamma doses from deposited radioactive material

The external gamma dose from radioactive material deposited on the ground to a person located at a given point is found by integrating the dose contributions from the individual part-elements of the ground. In the calculation it is assumed that the ground can be considered as an infinite, plane source, where the radioactive material is deposited with a constant density corresponding to the density on the ground immediately under the point in question. The dose is calculated in points that lie 1 m above the ground.

The dose will be:

$$(21)\quad D_S(x,y,s,u) = 0.2304 \cdot \sum_{k=1}^{n_e} E_k^\gamma \cdot Ex(\mu(E_k^\gamma)\cdot 1)\cdot \mu_{en}(E_k^\gamma) \cdot \sum_{i=1}^{n_{iso}} f_{k,i} \cdot \int_{te_1}^{te_2} W_i(x,y,s,u,t,td_1,td_2)\,dt$$

where

$D_S(s,y,s,u)$ = the external gamma dose 1 m above the ground from the radioactive material deposited on the ground [rem]

$\mu_{en}(E_k^\gamma)$ = the linear energy absorption coefficient for air for the photon energy E_k^γ [m^{-1}]

$\mu(E_k^\gamma)$ = the linear attenuation coefficient for air for the photon energy E_k^γ [m^{-1}]

k = energy group number ($1 \leq k \leq 8$)

i = isotope number

n_{iso} = number of isotopes

n_e = number of energy groups

E_k^γ = mean photon energy for energy group no. K

$f_{k,i}$ = photon yield for isotope no. i in the k'th energy group

$$Ex(\tau) \equiv \int_\tau^\infty \frac{e^{-\rho}}{\rho} d\rho$$

$W(x,y,s,u,t,td_1td_2)$ = the concentration of isotope no. i (Ci/m^2) on the ground vertically under the detector point at the time t, when the deposition takes place in the period of time from td_1 to td_2 (see otherwise sec. 1.5).

te_1 = start of exposure [s]

te_2 = termination of exposure [s]

td_1 = start of deposition [s]

td_2 = termination of deposition [s]

It should be noted that expression (21) does not take into account the shielding effect resulting from the roughness of the ground or the dose build-up in the air medium between the detector point and the ground.

3. DATA

This section gives a brief survey of some of the data included in the computer program set up on the basis of the model.

3.1. Dispersion parameters

The atmospheric stability is classified by the six Pasquill classes A - F [5,2]. For these stability classes, use is made of Turner's [2] ten-minute mean values for the dispersion parameters ($\sigma_y(x,s)$ and $\sigma_z(x,s)$).

3.2. Effective stack height

The effective stack height, H, is assumed to be constant and thus independent of the distance from the point of release. Thermal lift of the released activity is calculated on the basis of Briggs' formula (appendix 1, sec. 1.5 of this report). The calculation of the lift does not take decay heat and the latent heat of the accompanying steam into account.

3.3. Daughter products

In calculating the external gamma doses both from airborne and from deposited radioactive material, use is made of the following, simplified decay chains:

	Mother product		Daughter product
a.	Kr 85 m	→	Kr 85
b.	Kr 88	→	Rb 88
c.	Kr 89	→	Rb 89
d.	Sr 90	→	Y 90
e.	Sr 91	→	Y 91
f.	Zr 95	→	Nb 95
g.	Zr 97	→	Nb 97
h.	Mo 99	→	Tc 99 m
i.	Ru 105	→	Rh 105
j.	Ru 106	→	Rh 106
k.	Te 129 m	→	Te 129
l.	131 m	→	Te 131

(continued)

	Mother product		Daughter product
m.	Te 132	→	I 132
n.	Sb 127	→	Te 129 m
o.	I 131	→	Xe 131 m
p.	I 133	→	Xe 133
q.	I 135	→	Xe 135
r.	Xe 133 m	→	Xe 133
s.	Xe 135 m	→	Xe 135
t.	Xe 137	→	Cs 137
u.	Xe 138	→	Cs 138
v.	Ba 140	→	La 140
w.	Ce 143	→	Pr 143
x.	Ce 144	→	Pr 144
y.	Nd 147	→	Pm 147
z.	Np 239	→	Pu 239

3.2. Depositability

Argon-41 and all the krypton and xenon isotopes are reckoned not to be depositable. The other isotopes in question are reckoned to be depositable.

3.3. Data for calculating external gamma doses

3.3.1. Gamma energy groups

The division of energy groups shown in table 1 is found appropriate when calculating the external gamma doses (11).

Table 1

Photon energy groups

Group number	Energy limits (MeV)	Mean energies (MeV)
1	0-0.080	0.04
2	0.081-0.150	0.12
3	0.151-0.250	0.20
4	0.251-0.510	0.38
5	0.511-0.850	0.68
6	0.851-1.330	1.09
7	1.331-2.030	1.68
8	2.031-3.000	2.53

3.3.2. The distribution of the photon yields of the isotopes over the energy groups

Table 2

The photon yield of the isotopes in energy groups

Isotope	Energy group number							
	1	2	3	4	5	6	7	8
Ar 41						1.00		
Kr 83 m	0.09							
Kr 85 m		0.74		0.13				

(continued)

Isotope	Energy group number							
	1	2	3	4	5	6	7	8
Kr 87				0.84	0.16			0.35
Kr 88			0.42	0.05	0.23		0.14	0.53
Kr 89			0.31	0.99		0.55	0.70	0.42
Rb 88						0.13	0.21	0.02
Rb 89					0.17	1.29		0.27
Sr 91					0.42	0.33	0.05	
Zr 95					0.98			
Zr 97					0.92			
Nb 95					1.00			
Nb 97					1.00			
Mo 99	0.02		0.07	0.01	0.16			
Tc 99m		0.90						
Ru 103				0.88	0.06			
Ru 105				0.43	0.64			
Rh 105				0.24				
Rh 106				0.21	0.11	0.03		
Te 129m					0.06			
Te 129	0.19			0.17	0.01	0.02		
Te 131m	0.02	0.05	0.16	0.09	0.91	0.24	0.06	
Te 131		0.68		0.21	0.04	0.13		
Te 132	0.17		0.90					
I 131	0.03			0.87	0.09			
I 132			0.01		2.53	0.35	0.17	
I 133					0.90			
I 134		0.03		0.08	1.21	0.76	0.14	
I 135				0.07		0.91	0.42	
Xe 131m			0.02					
Xe 133m			0.14					
Xe 133	0.37							
Xe 135m					0.80			
Xe 135			0.91		0.03			
Xe 137				0.33				
Xe 138				1.32			0.65	
Cs 134					2.20	0.03	0.03	
Cs 136	0.11	0.06	0.36	0.71	1.00	1.02		

(continued)

Isotope	Energy group number							
	1	2	3	4	5	6	7	8
Cs 137					0.85			
Cs 138				0.23	0.08	0.25	0.73	0.27
Ba 140	0.11		0.06	0.11	0.34			
La 140				0.60	0.19	0.10	0.96	0.03
Ce 141		0.48						
Ce 143	0.11			0.48	0.15	0.02		
Ce 144	0.02	0.11						
Pr 144					0.02			
Nd 147		0.28		0.20				
Pm 149				0.02				
Pu 238								
Pu 239								
Pu 240								
Pu 241								
Ru 86						0.088		
Te 127m								
Te 127								
Sb 127				0.45	0.66	0.012		
Sb 129			0.029	0.084	0.75	0.44	0.093	
Np 239		0.23	0.16	0.14				
Am 241	0.36							
Cm 242								
Cm 244								

Source: references 8, 9 and 11

Note: Photon yields below 1% (0.01) are not included in the table or in the calculations of external gamma radiation doses.

3.3.3. Dose build-up factor, energy absorption coefficient and linear attenuation coefficient for air for energy groups

Table 3

Data for energy groups

Energy group no.	Energy absorption coefficient, $(\frac{\mu_{en}}{\rho})$ $(cm^2\ g^{-1})$	Linear attenuation coefficient $\mu(m^{-1})$	Dose build-up factor coefficient K_E
1	6.57 E-2	3.15 E-2	2.70
2	2.40 E-2	1.89 E-2	5.10
3	2.71 E-2	1.60 E-2	3.57
4	2.94 E-2	1.28 E-2	2.37
5	2.93 E-2	9.99 E-3	1.64
6	2.73 E-2	7.90 E-3	1.24
7	2.47 E-2	6.30 E-3	0.97
8	2.17 E-2	5.00 E-3	0.79

Source: references 10 and 11.

Note: The build-up factor is defined as $B_E(r) = 1+K_E \cdot \mu \cdot r$,

where $$K_E \equiv \frac{\mu-\mu_{en}}{\mu_{en}}$$

3.4. Dose-conversion factors for inhaled isotopes

Dose-conversion factors giving the relation between the amount of a given isotope which is inhaled and the resulting dose to the organ in question, integrated from the time of the passage of the plume and until a given number of days after this time, are taken from WASH-1400 [3, table D-2].

Use is made of the following integration periods in the models:

Bone marrow	30 days
Lungs	365 days (1 yr)
GI tract	7 days
Thyroid gland	30 days

The dose-conversion factors for the bone marrow are calculated as the dose-conversion factor for the period 7 days plus 0.5 times the dose-conversion factor for the period from 8 to 30 days after exposure. The dose-conversion factors thus calculated can hence be used for calculations of early and continuing somatic effects [3, sec. 9.2.2.1].

The breathing rate for adults is assumed to be $3.5 \cdot 10^{-4}$ m^3/s.

REFERENCES

1. Thykier-Nielsen, S.: Modeller til beregning af eksterne gammadoser og inhalationsdoser fra frigørelser til atmosfæren af radioaktive stoffer, Risø-M-1725 (1974) 48 pp. Errata til Risø-M-1725 (1974) 6 pp.

2. D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates. (National Air Pollution Control Association, Cincinatti, Ohio, (1969). (Public Health Service Publication No. 999-AP-26) 84 pp.

3. Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, Appendix VI, Wash-1400 (NUREG-75/014) USNRC, 1975.

4. D.H. Slade (editor), Meteorology and Atomic Energy - 1968. TID-24190 (1968) 415 pp.

5. F. Pasquill, The Estimation of the Dispersion of Windborne Material. Meteorol. Mag., 90 (1961) 33-49.

6. A.J. Brook, The Effect of Deposition on the Concentration of Windborne Material, AHSB(S)-R 157 (1968) 9 pp.

7. J.R. Beattie and P.M. Bryant, Assessment of Environmental Hazards from Reactor Fission Product Releases, AHSB(S)R-135 (1970) 54 pp.

8. C.M. Lederer, J.M. Hollander, and I. Perlman, Table of Isotopes. 6. edition (Wiley, New York, 1967) 594 pp.

9. Handbook of Chemistry and Physics, 55 ed. (CRC Press Inc., Cleveland, Ohio, 1974).

10. Radiological Health Handbook. Revised edition. (U.S. Department of Health, Education and Welfare, Public Health Service, Rockville, Md., 1970). (Public Health Service Publication, 2016) 458 pp.

11. Fenger, J.: Isotopdata for beregning af eksterne gammadoser og inhalationsdoser (Risø, 1975).

12. F.A.Gifford, The Rise of Strongly Radioactive Plumes. Appl. Meteorol 6 (1967) 44-49.

APPENDIX 3

METEOROLOGY

by

Erik Lundtang Petersen

1. ATMOSPHERIC DIFFUSION

1.1. The Gaussian diffusion model in general

The radioactive materials that are released to the atmosphere as a result of an accident at a nuclear power station will be carried by the wind and spread like a smoke plume. The transport and the mixing of the materials will be determined by the state of the atmosphere along the direction of diffusion, by the topography of the area, and by the properties of the materials released. The wind direction, wind speed, and the vertical temperature gradient are the most important atmospheric parameters, because they determine transport direction, dilution at the moment of release and the turbulent mixing.

The so-called Gaussian diffusion model, which is the basic diffusion model in WASH-1400 and in this study, is a method for describing how a smoke plume spreads in the atmosphere. Although this model has numerous weaknesses, it is today the most used method in practical calculations of the plume from single sources. This is partly because, in its simplest form, it only requires meteorological measurements at one point, and partly because the diffusion parameters ascribed to the model incorporate much empirical knowledge of the behaviour of plumes, so that the theoretical weaknesses of the model are often compensated for.

The diffusion conditions that most resemble the idealised assumptions behind the model are characterised by a diffusion over a horizontal homogeneous terrain to a distance of several km from the source, for source heights of less than 100 - 200 m, for stability conditions that are neither extremely stable nor unstable, with a moderate wind, and for measurements with averaging times from 10 to 60 min. Experiments to verify the model carried out under such conditions have shown that it should be able to forecast concentrations within a factor of 2-3 [1 and 2]. Use of the Gaussian model in cases where these conditions are not fulfilled is based on extrapolations that attempt to include our knowledge about diffusion in the atmosphere.

The diffusion parameters σ_z and σ_y used in the model are functions of distance from the point of release and of the atmospheric stability. (For a definition of σ_y and σ_z, see

appendix 1. The width of the plume is $\sim 3\sigma_y$). The dependance on stability is given by seven discrete stability categories - the so-called Pasquill categories - which can each be specified either by a temperature variation over the lowest 100 m of the atmosphere as given in table 3.1 [1] or by a classification according to solar radiation, cloud cover and wind speed [3].

The meteorological data for Risø and Gladsaxe are classified according to the first method and the data from Kastrup and Værløse according to the second method. The methods are not entirely comparable because the latter categorizes all cases with wind speeds greater than 6 m/s as C or D, for which reason these categories will have a relatively large frequency when calculated by this method. This appears clearly from the later discussed tables 3.2, 3.3 and 3.4.

Table 3.1

Categories of atmospheric stability

Description	Category	T(100 m) - T(0) m
very unstable	A	< -1.9
unstable	B	-1.9 to -1.7
rather unstable	C	-1.7 to -1.5
neutral	D	-1.5 to -0.5
rather stable	E	-0.5 to 1.5
very stable	F + G	< 1.5

The system of stability categories defined on the basis of routine meteorological measurements has been introduced as a convenient substitute for turbulence measurements. Direct turbulence measurements would give a more reliable indication of the diffusion conditions in the atmosphere, but such measurements are still too specialized and complex to be carried out routinely.

1.2. The influence of averaging time on the time-mean concentration

A plume can be considered as a succession of elementary sections that behave like individual puffs. It is obvious that

the amount of material contained in an element of the plume of a given length in the wind direction will be inversely proportional with the wind speed. Diffusion perpendicular to the wind direction, horizontally and vertically, increases with distance from the source under the influence of small-scale movements.

Trajectories of successive sections of the plume are not identical, but are diffused irregularly by large-scale movements in the flow. This results in a progressive extending of the dimensions of the plume perpendicular to the direction of diffusion. The average concentration found downstream from a source point thus decreases not only with distance from the source but also with exposure time. This is an important property of the time-mean concentration, a property that essentially results from the fact that there are movements in the flow on a scale that is larger than the cross section of the plume.

Both types of diffusion, large- and small-scale, are introduced into the Gaussian diffusion model by the diffusion parameters. As these are experimentally determined by mean times from 10 to 60 min, it is obvious that if they are used for determination of the time-mean concentration over a considerably longer period of time - e.g. corresponding to the three-hour release of a BWR2 and a BWR3 accident - the concentrations calculated will be too large, all other things being equal.

WASH-1400 takes this into account by increasing the horizontal diffusion by a factor (averaging time/half hour)$^{1/3}$.

If no account is taken of the possible over-estimation of the concentrations in the case of long averaging times, it is found that the largest bone marrow doses calculated at 20 km distances from the source apply to a BWR2 accident - Pasquill category F. A survey of the overestimation is given in the following.

In extremely stable weather conditions, Pasquill categories F + G, turbulence is weak, and thus also the small-scale diffusion. For short averaging times, 10 to 60 min, the concentration in the plume will fall very slowly with distance from the source as the width and height of the plume only change very slowly. For longer averaging times, large-scale diffusion caused by large horizontal eddies will give a dominant contribution to the diffusion. The large eddies will give the plume

a strongly meandering course.

An observer standing still downstream of the source will, as the plume gradually passes, alternately find himself between the meanders and in the narrow plume. A realistic calculation of the average concentration to which the observer is subjected clearly requires that the meandering effect is taken into account: i.e. to the σ_y, which corresponds to small-scale diffusion and which is approximately equal to that found from the formula set used [2], should be added a σ_{ym} corresponding to large-scale diffusion. The horizontal diffusion is then determined by

$$\sigma_{y_{total}} = \sqrt{\sigma_y^2 + \sigma_{ym}^2} \quad . \tag{1}$$

as an approximative expression for σ_{ym} can be found from the statistical diffusion theory [3]:

$$\sigma_{ym}^2 = 2\ \sigma_v^2\ J_L^2 \left(\frac{x}{UJ_L} - 1 + \exp(-\frac{x}{UJ_L}) \right) \left(1+2\ \frac{J_E}{T} \right)^{-1} \tag{2}$$

where

- x is the distance from the source to the measuring point, m.
- T is the averaging time, s.
- U is the mean wind speed in the mean wind vector direction (over the time T), m s^{-1}.
- σ_v^2 is the variance of the component of the wind vector perpendicular to the mean wind direction, m^2 s^{-2}.
- J_L is the Lagrangian time-scale, which is a characteristic time for the large eddies, s.
- J_E is the Eulerian time-scale, which is a characteristic time for the atmospheric movements observed from the point of release, s.

One year's data (1975) from Risø's meteorological tower was searched for weather situations of type Pasquill F + G with a duration of at least 3 h and a wind speed between 1 and 3 m s^{-1}.

The measurements are 10 min mean values: wind direction and speed are measured at a height of 117 m. A total of 12 situations were found, and for each of them σ_v and U were calculated. The result is shown in table 3.5. Figure 3.2 shows the component of the wind vector perpendicular to the mean wind direction. It appears from the figure that in several cases there is a uniform turning of the wind direction, a phenomenon which will plainly make σ_{ym} much larger in relation to σ_y.

As a calculation example, we take case no. 8 which, if the wind direction had been more easterly, is the weather situation that gives the largest calculated bone marrow doses in Copenhagen as a result of a BWR2 accident to the Barsebäck reactor when not taking into account the meandering effect.

Table 3.5 gives $\sigma_v = 0.47$ m s^{-1} and U = 1.99 m s^{-1}. J_E is estimated on the basis of Fig. 3.2 to be 1 h, and J_L must be equal to the distance between Copenhagen and Barsebäck divided by U, i.e. $\sim$ 3 hours. Inserted in (2), this gives $\sigma_{ym} \sim 3000$ m, in comparison with the $\sigma_y = 500$ m used in the calculations, which means that the diffusion is underestimated by a factor of 6.

To find out if this effect is just as intense over water, we made a corresponding investigation of 12 days' data from an experiment in the Kattegat. A tower with a height of 15 m above the water surface was erected 50 m from the nearest coast. The result of the investigation is seen in Table 3.6, Fig. 3.3. The conclusion is that, for these data, the meandering effect is just as pronounced as that found over land.

2. Statistics

The statistical analysis in this section builds on the assumption that in an accident at Barsebäck the radioactive material would be released to the atmosphere during a period of time of less than one hour. The release can thus be characterised by a puff - and the diffusion of this puff can be calculated by means of the Gaussian diffusion model. This assumption is in agreement with WASH-1400.

The meteorological variables, wind speed, wind direction and temperature, are assumed to be uniform at any point within a suitably large geographical area and in such a way as they have been measured hour by hour at Risø and Kastrup, respectively.

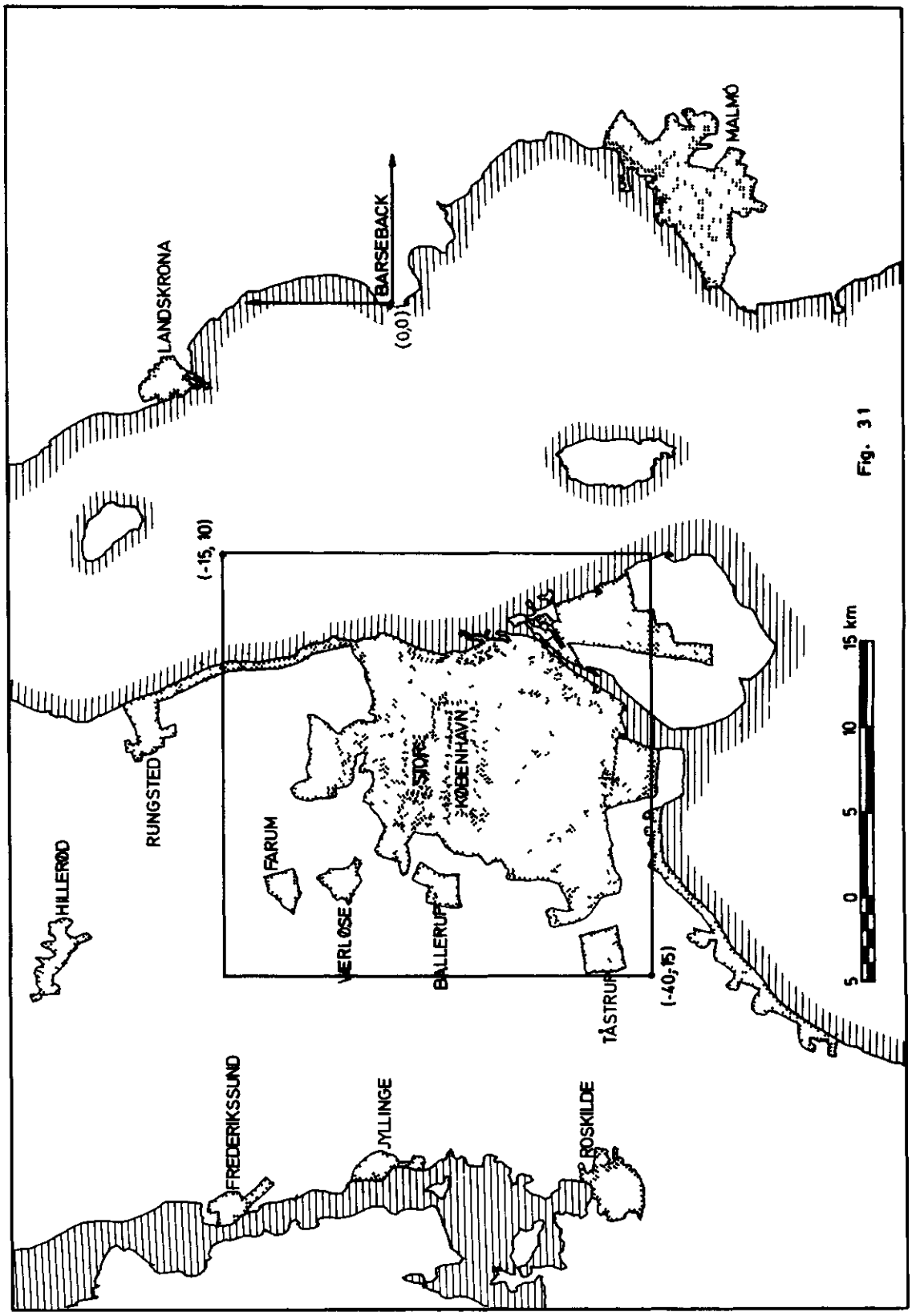

MALMÖ
BARSEBACK
(0,0)
LANDSKRONA
(-15, 10)
RUNGSTED
HILLERØD
FARUM
VÆRLØSE
STOR-
KØBENHAVN
BALLERUP
TÅSTRUP
(-40, 15)
FREDERIKSSUND
JYLLINGE
ROSKILDE
5
0
5
10
15 km

Fig. 31

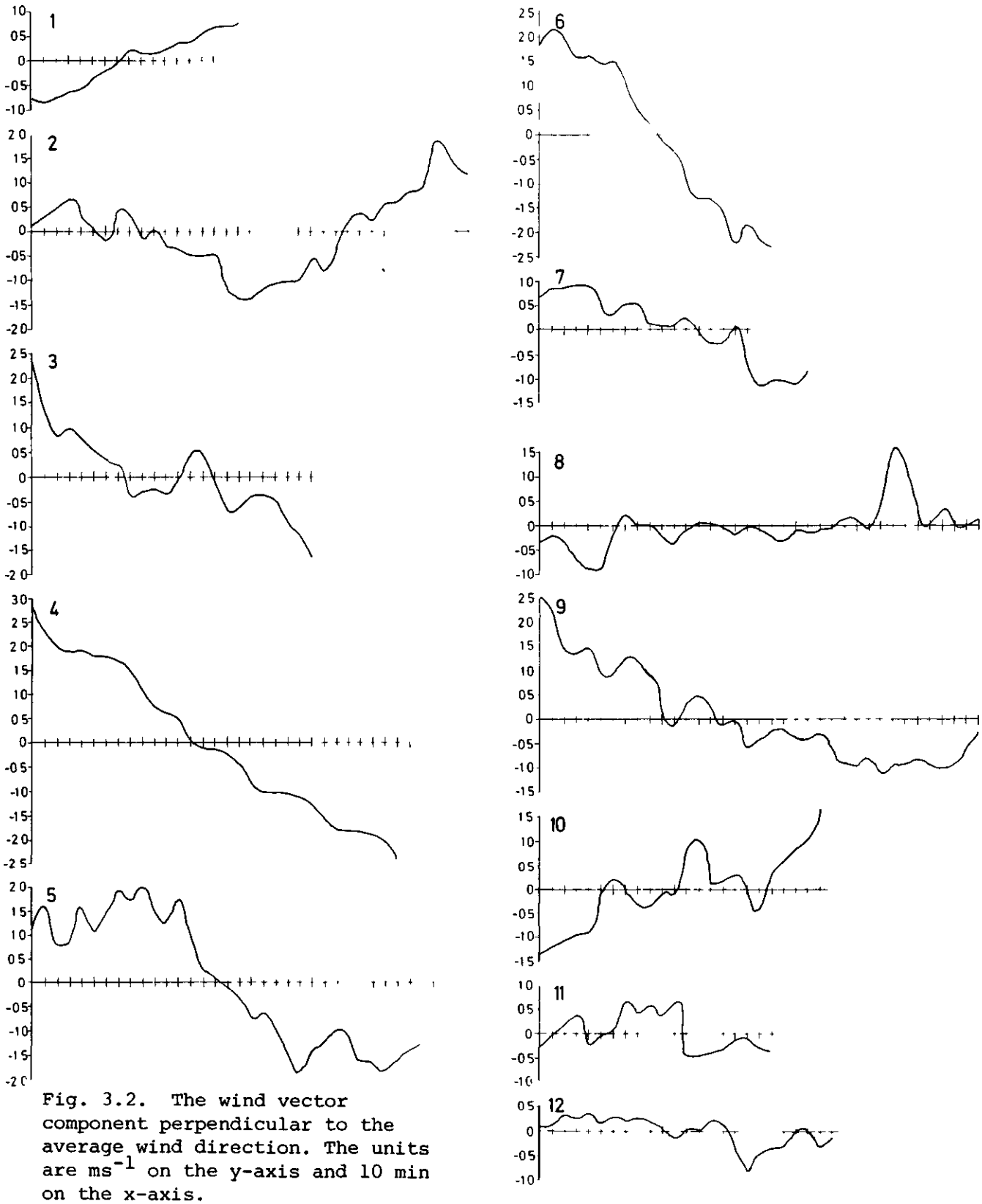


Fig. 3.2. The wind vector component perpendicular to the average wind direction. The units are ms^{-1} on the y-axis and 10 min on the x-axis.
The numbering is referring to table 3.5. Risø data (dispersion over land land).

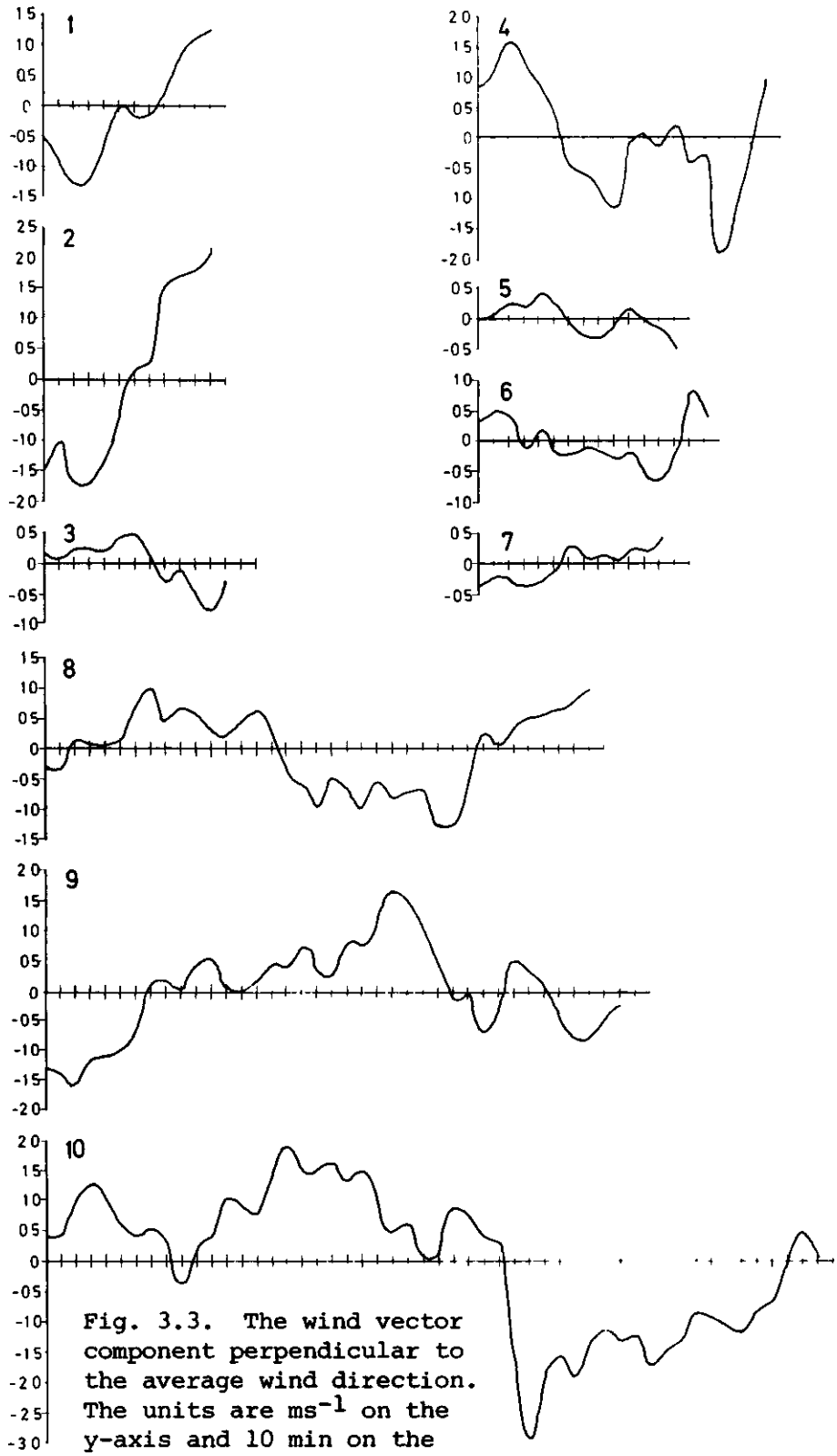
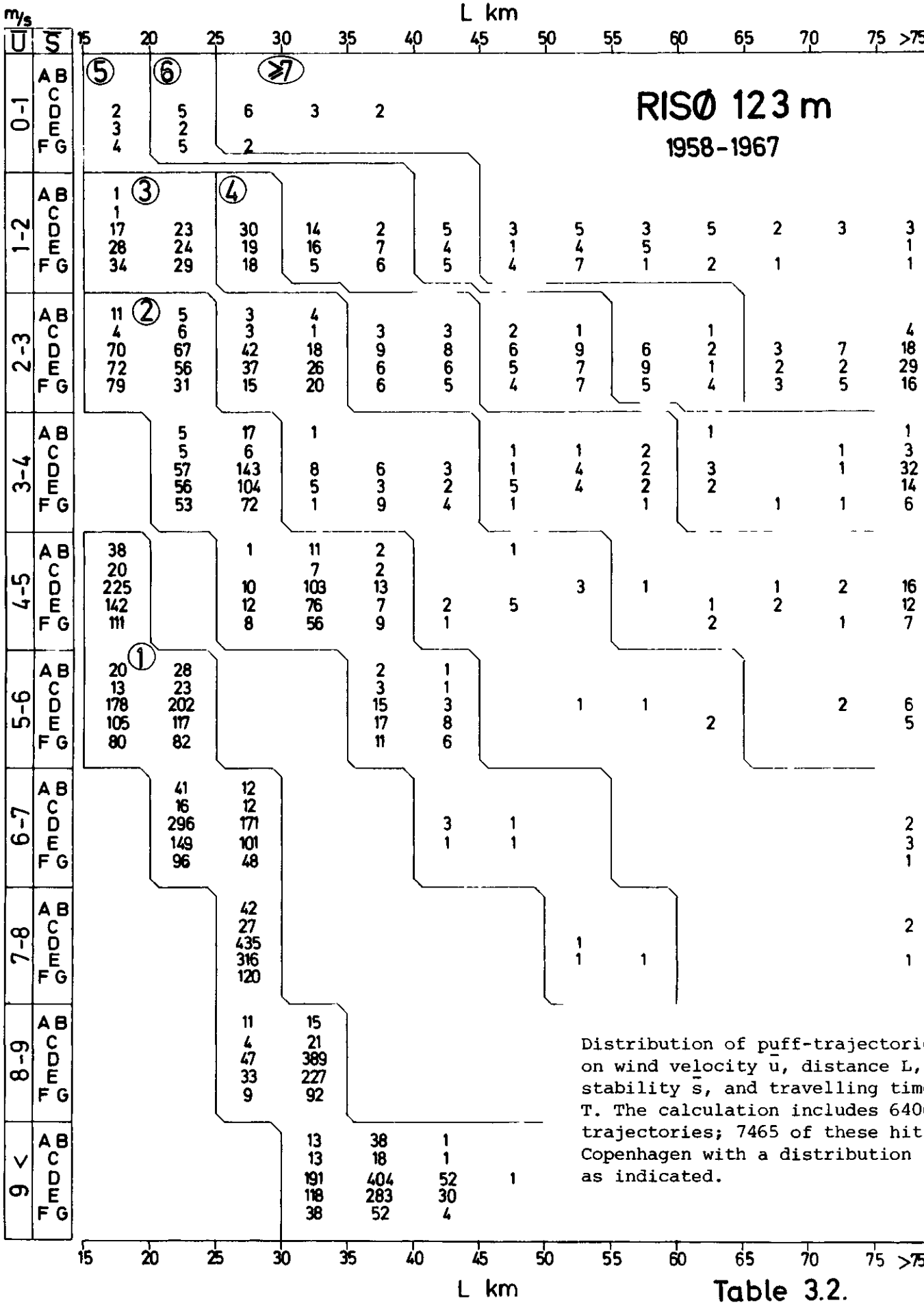


Fig. 3.3. The wind vector component perpendicular to the average wind direction. The units are ms^{-1} on the y-axis and 10 min on the x-axis.
The numbering is referring to table 3.6. Kattegat data (dispersion over water).



Distribution of puff-trajectories on wind velocity ū, distance L, stability s̄, and travelling time T. The calculation includes 64067 trajectories; 7465 of these hit Copenhagen with a distribution as indicated.

Table 3.2.

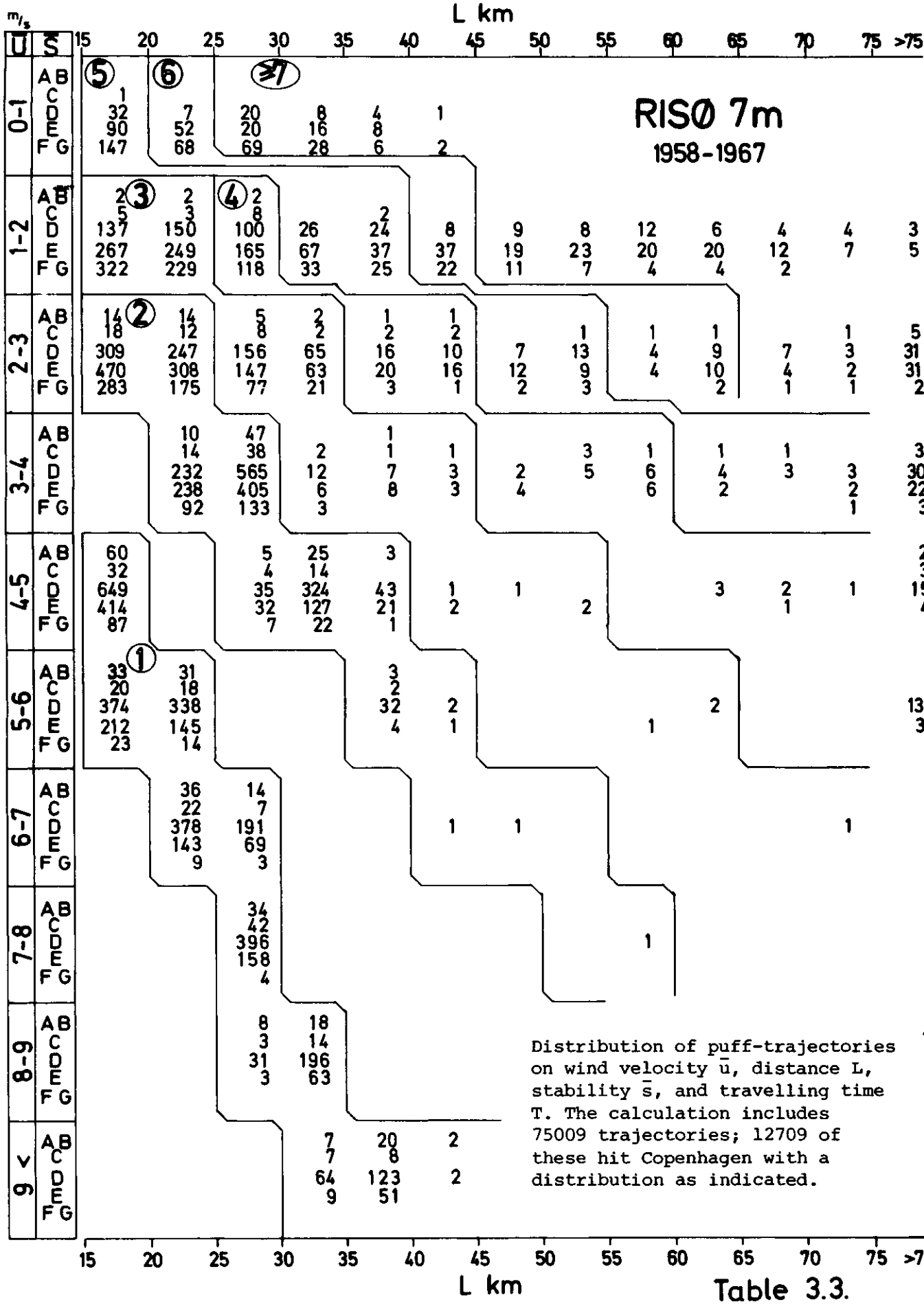
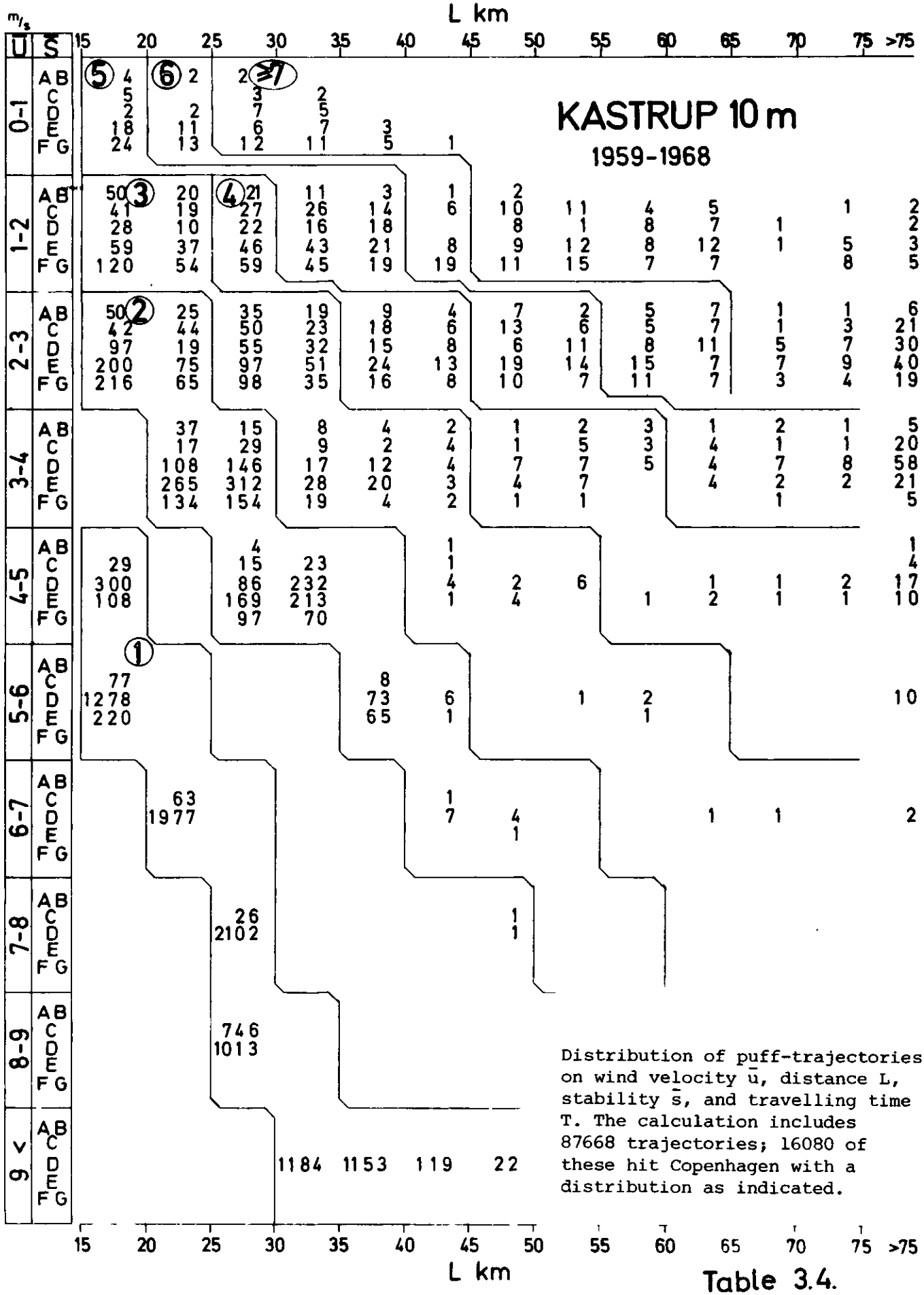

RISØ 7m
1958-1967
L km
ū m/s
s̄
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9 <
A B
C
D
E
F G
15 20 25 30 35 40 45 50 55 60 65 70 75 >75
Distribution of puff-trajectories on wind velocity ū, distance L, stability s̄, and travelling time T. The calculation includes 75009 trajectories; 12709 of these hit Copenhagen with a distribution as indicated.

Table 3.3.



Distribution of puff-trajectories on wind velocity ū, distance L, stability s̄, and travelling time T. The calculation includes 87668 trajectories; 16080 of these hit Copenhagen with a distribution as indicated.

Table 3.4.

Table 3.5

Characteristics of the twelve cases occurring in 1975 with stability category F + G and a wind speed between 1 and 3 m/s for at least three consecutive hours. Data from Risø's meteorology tower.

Case number	1	2	3	4	5	6	7	8	9	10	11	12
Duration in minutes	180	370	240	310	330	200	230	410	430	240	200	250
Mean wind speed m/s	1.17	1.16	1.96	1.69	1.69	1.89	2.43	1.99	2.28	2.09	1.51	1.74
Mean direction degrees	73	58	90	235	200	92	338	36	102	196	220	24
STDV * m/s	0.53	0.84	0.84	1.51	1.33	1.56	0.68	0.47	0.91	0.75	0.36	0.28

* The standard deviation of 10 min mean values of the wind vector component perpendicular to the mean wind direction.

Table 3.6

Characteristics of the cases occurring in the period 28/5-10/6 1973 with stable temperature gradient and a wind speed less than or equal to 3 m/s for at least 3 consecutive hours. Data from the meteorology tower in the Kattegat.

Case number	1	2	3	4	5	6	7	8	9	10
Duration in minutes	180	180	195	300	210	240	195	555	585	825
Mean wind speed m/s	1.44	1.30	2.32	2.12	2.14	2.84	2.27	2.08	2.10	0.91
Mean direction degrees	151	234	216	312	312	225	235	246	347	130
STDV * m/s	0.83	1.39	0.80	0.93	0.34	0.40	0.84	1.51	2.00	1.06

* The standard deviation of 15 min mean values of the wind vector component perpendicular to the mean wind direction

Barsebäck is located in the middle of the area and Copenhagen is approximated by the 25 x 35 km rectangle given in Fig. 3.1. The smallest distance to Barsebäck is, conservatively reckoned, 15 km. Imagining that a puff is released from Barsebäck each hour, the question is how many puffs would reach Copenhagen in the course of 10 years. Each puff moves along a trajectory reckoned on the basis of wind speed and direction. If the puff hits Copenhagen within 12 h of the release, the transit time T is registered, and a temporal mean wind speed $\bar{u}$ and a temporal mean stability $\bar{S}$ are reckoned along the trajectories. For the Risø data, the stability is reckoned on the basis of temperature measurements at 56 and 6 m heights and converted to a discrete category according to table 3.1. For the Kastrup data, the stability is determined as described in section 1.1.

Thus each puff whose trajectory hits Copenhagen is characterised by three figures; namely, 1) transit time T, 2) mean wind speed $\bar{u}$, and 3) mean stability $\bar{s}$. The trajectory length L is obtained from $L = T \cdot \bar{u}$, a length that can be considered as an equivalent distance between Barsebäck and Copenhagen. Together with $\bar{u}$ and $\bar{s}$, this distance can be used in a stationary Gaussian model. L cannot be less than 15 km.

Tables 3.2, 3.3 and 3.4 show the result of the calculations for Risø at the heights 123 and 7 m and from Kastrup at 10 m. From the 10 years' data 64067, 75009, and 87668 trajectories could be calculated, respectively, and of these 7645, 12709 and 16080, respectively, hit Copenhagen with a distribution of $\bar{u}$, $\bar{s}$, L and T, as given. The figures are arranged according to semi-open intervals of $\bar{u}$ and L, and within these intervals according to five stability categories, as A and B as well as F and G are combined. The mean wind intervals $0 < \bar{u} \leq 1$, ..., 9 m/s $< \bar{u}$ are plotted vertically downwards and the trajectory intervals $15 < L \leq 20$, ..., $L > 75$ km are plotted horizontally. The relation $L = T\bar{u}$ is depicted as a straight line, which is seen in the table as a "stairway-like" band. The figures marked by a circle give the transit time T.

As an example, we can calculate the probability

$$P(1 < \bar{u} \leq 2,\ \bar{s} = FG,\ 15 < L \leq 25) \times P(\text{puff hits Copenhagen})$$

i.e. the probability that a puff hits Copenhagen and that it has

moved at a mean speed of between 1 and 2 m/s along a track that is between 15 and 25 km long, and under atmospheric conditions that correspond to stability category F or G. The probability will be:

Risø	123 m:	(34+29)/64067 ∿ 0.001
Risø	7 m:	(322+229)/75009 ∿ 0.007
Kastrup	10 m:	(120+54)/87668 ∿ 0.002

The above figures, as well as the figures in the three tables as a whole, show that there are significant differences between the measurements. One of the reasons for this is that the methods for determining stability are not the same for Risø and for Kastrup.

As discussed in Sec. 1.1, this means that categories C and D are determined with a relatively larger frequency for Kastrup.

The measuring height is also seen to have much influence, which is because the wind speed over the land, at the height of 100 m is on average 1.5 times the speed at the height of 10 m. In addition, the wind direction turns with height, an effect which is particularly pronounced in the lowest 100 m of the atmosphere in stable weather situations [4].

REFERENCES

1. Onsite Meteorological Programs. Safety Guide 23 (USAEC, 1972).

2. Turner, D.B., Workbook of Atmospheric Dispersion Estimates. E.P.A. Office of Air Programs Publication. No. AP-26. 1972.

3. Pasquill, F., Atmospheric Diffusion. John Wiley and Sons, New York. 1974. 101-165.

4. Petersen, E.L., On the Kinetic Energy Spectrum of Atmospheric Motions in the Planetary Boundary Layer. Risø Report No. 285. 1975.

APPENDIX 4

FISSION PRODUCT INVENTORY OF THE BARSEBÄCK REACTOR

by

Per Hedemann Jensen and Frank Højerup

CALCULATION OF FISSION PRODUCT INVENTORY

The fission product inventory of a reactor that has been in operation for a given time can be calculated at Risø using the programs FIPO [1] and BEGAFIP [2]. FIPO can account for the core geometry and the fissile nuclide composition of the fuel, among other things. The neutron energy spectrum can be divided into a number of thermal, epithermal and fast neutron energy groups. On the basis of a data library containing the fission yields of the individual isotopes, the cross section and the decay constants, the present version of FIPO can calculate the core content of isotopes with a half-life greater than 10 h. The content can be calculated for a given burn-up. The program is presently being further developed for calculating the content of isotopes with half-lives of less than 10 h. The present version calculates the activity for a total of 166 isotopes.

BEGAFIP also accounts for the composition of fissile nuclides in the fuel. The content of c. 400 isotopes can be calculated for in-put values of the correction factor for the infinite resonance integral, which is a function of the core geometry, neutron flux conditions (thermal/epithermal and fast/(thermal + epithermal)), moderator temperature, total amount of fuel in the core, as well as the time distribution of the burn-up. Just as FIPO, BEGAFIP contains a data library for fission yields, cross sections, decay constants and branching ratios.

Calculations of the fission product inventory with FIPO (3) show that the difference between the build-up of fission products in a BWR and in a PWR is less than 10%. Further, there is good agreement between FIPO's results and the fission product inventory used in WASH-1400. Reasonable agreement is found for BEGAFIP's results, too, cp. table 4.1.

In the calculations in this report FIPO's results are used for isotopes with half-lives greater than 10 h. BEGAFIP's results are used for isotopes with half-lives of less than 10 h. The values given in WASH-1400 (4) are used for the transuraniums. Considering the different reactor effects, the activity of the transuraniums is reduced by the effect ratio 1700/3200. Table 4.2. shows the inventory of fission products and transuraniums used in a 1700 MWt BWR.

Table 4.1. Fission product inventory of a 3200 MWt BWR

	Activity [MCi]		
	WASH 1400 18 MWd/kg U	FIPO 18 MWd/kg U	BEGAFIP 11 MWd/kg U
Kr 85	5.60 E-01	4.86 E-01	6.30 E-01
Kr 85m	2.40 E+01	-	2.97 E+01
Kr 87	4.70 E+01	-	5.08 E+01
Kr 88	6.80 E+01	-	7.18 E+01
Rb 86	2.60 E-02	-	1.38 E-02
Sr 89	9.40 E+01	9.33 E+01	1.08 E+02
Sr 90	3.70 E+00	3.75 E+00	4.79 E+00
Sr 91	1.10 E+02	-	1.34 E+02
Y 90	3.90 E+00	3.84 E+00	4.82 E+00
Y 91	1.20 E+02	1.18 E+02	1.37 E+02
Zr 95	1.50 E+02	1.48 E+02	1.61 E+02
Zr 97	1.50 E+02	-	1.51 E+02
Nb 95	1.50 E+02	1.48 E+02	1.63 E+02
Mo 99	1.60 E+02	1.56 E+02	1.65 E+02
Tc 99m	1.40 E+02	-	1.45 E+02
Ru 103	1.10 E+02	1.17 E+02	1.02 E+02
Ru 105	7.20 E+01	-	5.65 E+01
Ru 106	2.50 E+01	2.16 E+01	2.58 E+01
Rh 105	4.90 E+01	6.19 E+01	5.28 E+01
Te 127	5.90 E+00	-	5.44 E+00
Te 127m	1.10 E+00	5.97 E-01	8.49 E-01
Te 129	3.10 E+01	-	2.91 E+01
Te 129m	5.30 E+00	4.24 E+00	4.79 E+00
Te 131m	1.30 E+01	1.16 E+01	1.15 E+01
Te 132	1.20 E+02	1.13 E+02	1.25 E+02
Sb 127	6.10 E+00	3.16 E+00	5.65 E+00
Sb 129	3.30 E+01	-	3.06 E+01
I 131	8.50 E+01	8.73 E+01	8.37 E+01
I 132	1.20 E+02	-	1.21 E+02
I 133	1.70 E+02	1.71 E+02	1.73 E+02
I 134	1.90 E+02	-	2.09 E+02
I 135	1.50 E+02	1.62 E+02	1.65 E+02
Xe 133	1.70 E+02	1.68 E+02	1.80 E+02
Xe 135	3.40 E+01	4.32 E+01	6.13 E+01
Cs 134	7.50 E+00	2.97 E+00	1.20 E+00
Cs 136	3.00 E+00	1.15 E+00	1.51 E+00
Cs 137	4.70 E+00	4.54 E+00	5.80 E+00
Ba 140	1.60 E+02	1.53 E+02	1.65 E+02
La 140	1.60 E+02	1.55 E+02	1.67 E+02
Ce 141	1.50 E+02	1.43 E+02	1.61 E+02
Ce 143	1.30 E+02	1.36 E+02	1.49 E+02
Ce 144	8.50 E+01	8.58 E+01	9.87 E+01
Pr 143	1.30 E+02	1.36 E+02	1.48 E+02
Nd 147	6.00 E+01	5.77 E+01	5.91 E+01
Np 239	1.64 E+03	1.53 E+03	-
Pu 238	5.70 E-02	-	-
Pu 239	2.10 E-02	2.18 E-02	-
Pu 240	2.10 E-02	1.95 E-02	-
Pu 241	3.40 E+00	3.97 E+00	-
Am 241	1.70 E-03	-	-
Cm 242	5.00 E-01	-	-
Cm 244	2.30 E-02	-	-

Table 4.2. Fission product inventory of the Barsebäck reactor

Isotope	Activity [MCi] T_K=0	T_K=2h	T_K=30h
Co 58	0.78	0.78	0.77
Co 60	0.29	0.29	0.29
Kr 85	0.45	0.45	0.45
Kr 85m +)	16.6	12.3	0.15
Kr 87 +)	29.9	10.0	0
Kr 88 +)	42.2	25.7	0.025
Rb 86	0.014	0.014	0.013
Sr 89	43.9	43.8	43.8
Sr 90	3.53	3.53	3.53
Sr 91 +)	75.3	65.3	8.78
Y 90	3.60	3.60	3.58
Y 91	56.5	56.5	55.7
Zr 95	75.1	75.1	74.1
Zr 97 +)	81.4	75.1	24.0
Nb 95	75.5	75.5	75.5
Mo 99	81.6	79.8	59.5
Tc 99m +)	77.4	77.2	61.9
Ru 103	66.9	66.9	66.9
Ru 105 +)	24.5	18.6	0.24
Ru 106	10.6	10.6	10.6
Rh 105	39.4	37.9	22.1
Te 127 +)	2.53	2.53	2.33
Te 127m	0.38	0.38	0.38
Te 129 +)	14.7	13.2	1.63
Te 129m	2.40	2.39	2.34
Te 131m	6.56	6.27	3.28
Te 132	60.3	59.2	46.0
Sb 127	1.85	1.82	1.47
Sb 129 +)	15.5	11.3	0.12
I 131	46.6	46.4	42.4
I 132 +)	62.9	63.5	51.1
I 133	90.1	84.0	33.0
I 134 +)	111.1	47.7	0
I 135	85.5	69.6	3.83
Xe 133	89.3	89.3	84.1
Xe 135	25.8	32.9	16.3
Cs 134	3.0	3.0	3.0
Cs 136	0.82	0.82	0.77
Cs 137	4.52	4.52	4.52
Ba 140	79.3	78.9	74.1
La 140	80.5	80.5	78.8
Ce 141	74.0	74.0	72.1
Ce 143	69.6	66.7	37.0
Ce 144	57.1	57.1	57.0
Pr 143	69.4	69.4	68.3
Nd 147	30.3	30.2	28.0
Np 239	901.2	883.8	624.8
Pu 238 ++)	0.03	0.03	0.03
Pu 239 ++)	0.01	0.01	0.01
Pu 240 ++)	0.01	0.01	0.01
Pu 241 ++)	1.80	1.80	1.80
Am 241 ++)	0.001	0.001	0.001
Cm 242 ++)	0.27	0.27	0.27
Cm 244 ++)	0.012	0.012	0.012

+) BEGAFIP
++) WASH 1400

REFERENCES

1. Leif Mortensen, The Fission Product Treatment in the CEB Unit Cell Burn-up Programme. Risø-M-1356.

2. J. Elkert et al., BEGAFIP, et program for beräkning af klyvningsprodukternes aktivitet, beta- och gammaeffekter. RF-72 374 (Studsvik).

3. F. Højerup, Fission Product Inventory in LWR's. RP-4-76. Reaktorteknikafdelingen Risø.

4. Reactor Safety Study. Calculation of Reactor Accident Consequences. Appendix VI. WASH-1400.

ISBN 87-550-0495-4